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DESIGN AND INTEGRATION ISSUES OF VISUALLY-COUPLED SYSTEMS(U)

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This document is the text of a short course presented at SPIE in 1992 and 1994 dealing with design and integration issues of visually-coupled systems (VCS). The VCS described are coomposed of a helmet-mounted display, a display image source, and a head helmet tracker.

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DESIGN AND INTEGRATION ISSUES OF VISUALLY-COUPLED SYSTEMS

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Visually-coupled systems (VCS) utilizing head-mounted displays (HMS) have been around as a fascinating and potentially powerful concept for several decades. However, the development and marketing of a fully successful VCS continues at a fully successful VCS continues at a frustratingly slow pace. The purpose of this course is to introduce the student to the VCS concept and provide a basic foundation for understanding the design trade-offs involved. HMD optical system approaches and design parameters will be discussed along with interrelated trade-offs and relationships with human visual capability. The selection of the image source and supporting electronics with the helmet-mounted sight, system integration, and applications will be covered. The course will also briefly cover existing HMD systems and future directions.

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SECTION I

INTRODUCTION TO VISUALLY-COUPLED SYSTEMS (VCS)

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INTRODUCTION

'A visually-coupled system (VCS) integrates the natural visual and motor skills of an operator with the machine he is controlling. The VCS operator visually searches for, finds, and tracks an object of interest. His line-of-sight is measured and used to aim sensors and/or weapons toward the object. Information related to his visual/motor task from sensors, weapons, or central data sources is fed back directly to his vision by special displays so as to enhance his task performance. Currently a helmet-mounted sight (HMS) is used to measure head position and line-of-sight and a helmet-mounted display (HMD) is used to feed back information to the eye. R&D efforts are underway to reduce size, weight, and increase performance of future VCS devices. Such advanced VCS concepts as eye position sensing/control and dual field of view sensors/displays are being explored for future improved man-machine integration.'

The above paragraph is part of the abstract for a document (Birt and Task, Eds., 1973) that recorded the first tri-service and industry symposium on VCS held at Brooks AFB, San Antonio, Texas in November 1972. As can be seen from this paragraph, the primary original concept for VCS was directed toward improved weapons systems (particularly for aircraft). The preface of this document traces some of the early efforts in VCS during the 1960s. In some ways, considerable progress has been made since that time, in other ways, it appears that many of the problems we had then are still with us today.

Papers presented at this symposium included advanced visor projection HMDs, holographic optics for HMDs, several head trackers including the magnetic tracker that was the forerunner of the popular devices available today, even a paper on a remote oculometer (for measuring eye position from several feet away). Although the focus of the meeting was primarily on military use of VCS, there were come component technologies and applications that were appropriate for commercial/ industrial applications. With continuing reductions in Department of Defense budgets, the commercial applications are going to have to be the driving force for the future of VCS (such as virtual reality).

COMPONENTS OF VCS

There are undoubtedly a number of ways to subdivide a visually-coupled system. For purposes of this course we will divide VCS into three components: 1) the helmet-(or head-) mounted display (HMD), 2) the helmet (or head) tracker, and 3) the information/imagery source. The general concept of VCS is that the helmet/head/eye position change is sensed by the tracker indicating that the user has changed his direction of view which, in turn, causes the information/imagery source to change and provide different information/imagery to the user on the HMD. In such a system, the user is 'visually coupled' to the information/imagery source environment.

The information/imagery source could be a sensor mounted on a slewable platform (such as a TV camera or infra-red imaging systems) or it could a synthetic computer-generated imagery system, such as those used in producing imagery for large, domed simulators, or it may only be a symbol generator to change symbology based on look direction. The head/helmet tracking system can be mechanical, electro-optical, ultra-sonic or magnetic. Several systems have been tried over the years with the magnetic currently the most popular.

The HMD can be further subdivided into several subcomponents which will be discussed separately during this course. These subcomponents are: 1) optical system, 2) display, 3) display electronics, and 4) the mounting system. Although the mounting system (helmet and optical system support) will not be discussed in much detail, it is exceedingly important, since it determines the comfort and ease of adjustment for fitting the HMD to different individuals.

Table 1-1 summarizes the component structure of a VCS. Figure 1-1 is a graphic representation of the VCS concept.

Table 1-1.
The components of a visually-coupled system.

Head/helmet mounted display	Head/helmet trackers	Information/image sources
* Optical system	* Mechanical	* TV sensor
* Display	* Electro-optical	* Computer generated imagery
* Display electronics	* Ultra-sonic	* Symbol generator
* Mounting system	* Magnetic	

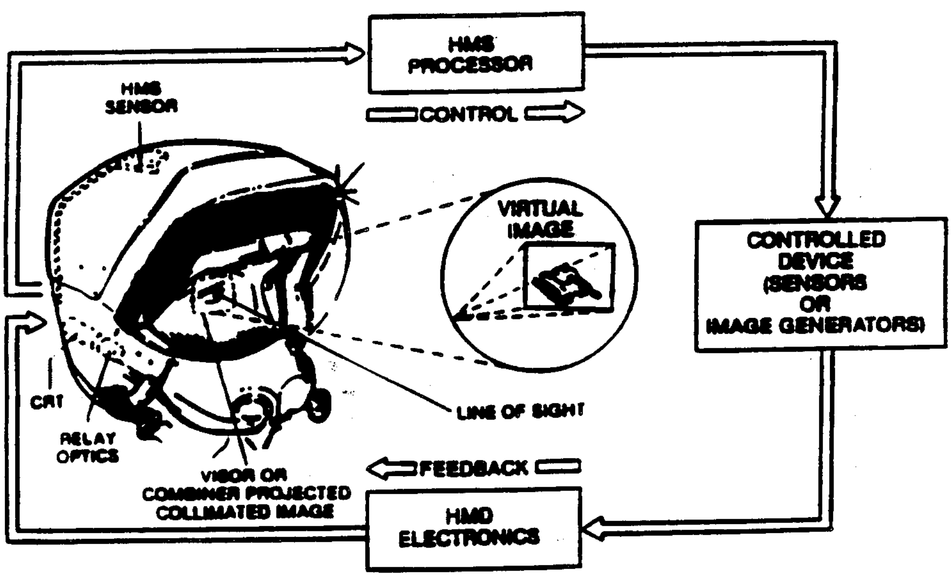

Figure 1-1. Schematic representation of visually-coupled system concept.

EXISTING SYSTEMS/APPLICATIONS

At the beginning of his presentation at the previously-referenced 1972 symposium on VCS, Cantanzaro (1973) showed a figure from a patent granted in 1916 for what must be considered as the first documented evidence for the beginning of the VCS concept. This figure has shown up in numerous presentations and papers since then. Since no short course would be complete without showing this basic approach to VCS, figure 1-2 is a copy of this infamous patent. It is apparent from this patent that the concept of VCS has been around for a long while. However, it is doubtful that the device disclosed in this patent ever became operational (or was even tested) due to some obvious physiological drawbacks.

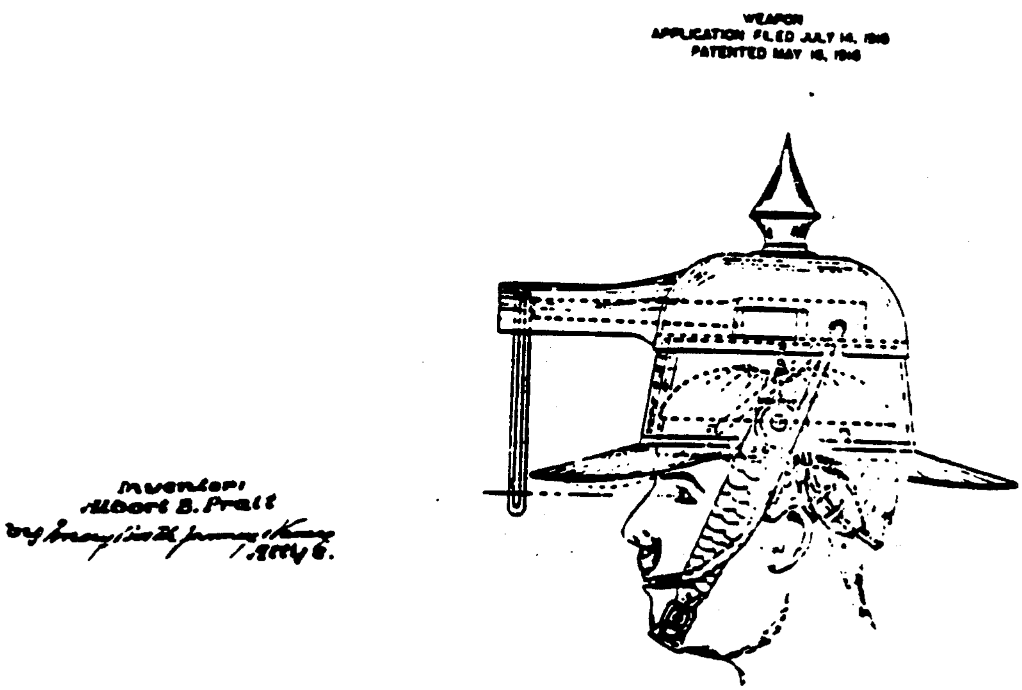

Figure 1-2. First known patent of a VCS based device.

Probably the first fully operational VCS was the Navy's VTAS (visual target acquisition system; Ferrin, 1973; Catanzaro, 1973) for the F-4 aircraft. Developed during the mid to late 1960s, it went through extensive testing demonstrating improved weapons lock-on by using the VCS concept. In this case, the tracker was a scanning infra-red light-fan-based system, the HMD was only a sighting reticle (two concentric circles, 10 milliradians and 50 milliradians in diameter) and four informational discretes. The information/imagery source in this case was a sidewinder missile seeker head with the feedback to the operator being whether or not the missile had locked onto its target. This feedback was provided by illuminating one of the discrete light sources located around and just outside of the outer circle of the reticle.

Currently, the only operational military VCS is the US Army Apache helicopter IHADSS (integrated helmet and display sighting system) which couples an infra-red sensor to a monocular HMD with a 40 degree field-of-view. The US Army Comanche helicopter is currently slated to have a binocular helmet mounted display (in development) and a visually-coupled biocular display has been under consideration for the US Air Force F-16 aircraft.

Many (several dozen) HMDs have been designed and built over the years for a number of programs, but the vast majority have been only prototype or demonstration models, and have not come close to being put into production. Some of these will be present/discussed during the presentation.

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Ferrin, J.J., 'F-4 visual target acquisition system,' in Birt J.A. and Task, H.L., Eds, A SYMPOSIUM ON VISUALLY COUPLED SYSTEMS: DEVELOPMENT AND APPLICATION, Brooks Air Force Base, San Antonio, Texas, 8-10 November 1972, published as AMD TR-73-1, September 1973, pp 33-37.

SECTION 2

QUICKIE REVIEW OF BASIC VISION AND OPTICS

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INTRODUCTION

The purpose of this section is to provide an extremely concise and limited 'micro-course' on key aspects of vision and optics to provide a background for the following sections relating to the helmet-mounted display (HMD) optical system and the optics/vision integration issues.

VISION

Figure 2-1 is a drawing of the human eye with many of the main parts labeled. Light comes through the cornea of the eye (which is where the majority of optical power of the eye comes from: the curvature of the cornea) and is focused (if properly corrected) onto the back part of the eye (the retina). The pupil of the eye (surrounded by the iris) is the part through which light passes to form the image on the retina. In bright light, the pupil becomes smaller (as small as 2-3 mm in diameter), since the retina doesn't need all the extra light and in low light levels (night time) the pupil opens up to 5-7 mm (or more if it is VERY dark) to allow the retina as much light as possible. When the pupil is small ('stopped down'), the eye is fairly close to diffraction-limited in its optical quality (assuming a normal, corrected eye). However, as the pupil opens up to let more light in, the optical quality degrades somewhat.

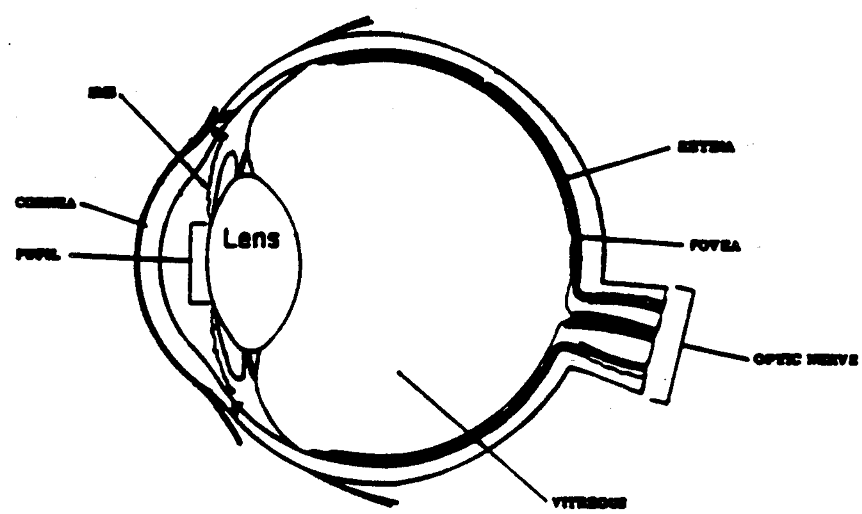

Figure 2-1. Schematic diagram of the eye

There are several physical aspects of the eye that are worth noting for future reference. First, the pupil of the eye is located approximately 3mm behind the cornea of the eye. This distance comes into play when determining the amount of physical eye

relief between the eye (corneal surface) and an optical system such as an HMD. Secondly, the eye rotates about a point approximately 13mm behind the corneal surface. Since this is a different location than the exit pupil, it means the eye pupil will appear to shift laterally as the eye rotates (Kocian, 1988). As will be discussed later, this has implications for the eye relief/exit pupil of the HMD.

Visual acuity is the ability of the eye to resolve (see) fine detail. Many different patterns have been used to measure visual acuity (Landolt 'C', tumbling 'E', Snellen letters, tri-bars, sine-wave gratings, square-wave gratings, Blackwell discs, checkerboards, etc.). Furthermore, visual acuity may be expressed in a number of different types of units, such as Snellen acuity (e.g., 20/20), cycles/degree, cycles/milliradian, arcminutes resolution, etc. The eye's visual acuity is greatest only for the fovea, which has an extremely high density of photo-receptors (cones) which occupies only a small fraction of the retina (about 2-3 degrees). Visual acuity decreases considerably away from the fovea and also reduces with lower light levels. A visual acuity of 1 arcminute is considered 'normal,' although most properly corrected individuals can see to a finer level of detail than this. One arcminute corresponds to 20/20 Snellen acuity, or 30 cycles/degree sine-wave grating spatial frequency. Visual acuity considerations have an important impact on HMD field-of-view and resolution trade-offs, as will be discussed in a later section.

Another feature of the eye that has a significant impact on HMD design is the crystaline lens of the eye. It is this component that changes optical power by changing shape to permit the eye to focus at different distances. This is referred to as accommodation. An individual's accommodative ability typically decreases with age until the lens can't change shape (optical power) at all. When this occurs, the eye is essentially set with a fixed focus at a fixed distance. The HMD design must take into consideration the age and visual accommodative ability of the individuals who will most likely be using it.

The above discussion was primarily directed at the characteristics of a single eye; however, most people have two eyes that must work in unison. This gives rise to another large set of factors that must be considered in the design of an HMD (see Section 6). Since the two eyes are located about 2 1/2 inches apart in the horizontal plane, each eye sees a slightly different image. The differences in these images are interpreted in the brain to provide depth information. This particular depth cue is referred to as stereopsis. It should be noted that there are many other monocular cues to depth besides stereopsis (such as paralax, occlusion, perspective, etc.). If the images seen by the two eyes are too much different, then the brain may not be able to fuse the disparate images into a single composite. When this occurs, the brain may see double images or may suppress part or all of one of the images in order to 'make sense' out of the disparate visual information. The eyes/brain can tolerate a certain amount of image disparity, but this amount varies from individual to individual.

For further information on the eye, see Graham (1965) or Cornsweet (1970).

OPTICS

Optical systems, such as helmet-mounted displays, are typically composed of a number of lens elements. Terminology can get somewhat confusing in that several lenses may be combined in such a way as to produce what is referred to as a single lens. For example, a camera lens is actually composed of many lenses/lens elements, but is simply referred to as a camera lens (singular) For purposes of this section, a lens

refers to an optical component which is capable of producing an image (real or virtual), of an object but may actually be composed on one or more lens elements.

Every lens has six special points along its optical axis which are called cardinal points. These are the front and back focal points, nodal points and principal points. Figure 2-2 is a drawing of a thick lens with the back principal point and the back focal point shown. For a lens in air the nodal points and the principal points are at the same location so, for HMD applications, the points of primary interest are the focal points and the principal points.

The focal length of the lens is the distance from the principal point to the focal point as marked in Figure 2-2. The back focal distance, however, is the distance from the last glass surface to the focal point. It is the focal length that is used to calculate the different optical design properties of the lens, but it is the back focal distance that determines physical clearance distance from the lens to objects placed at the focal point.

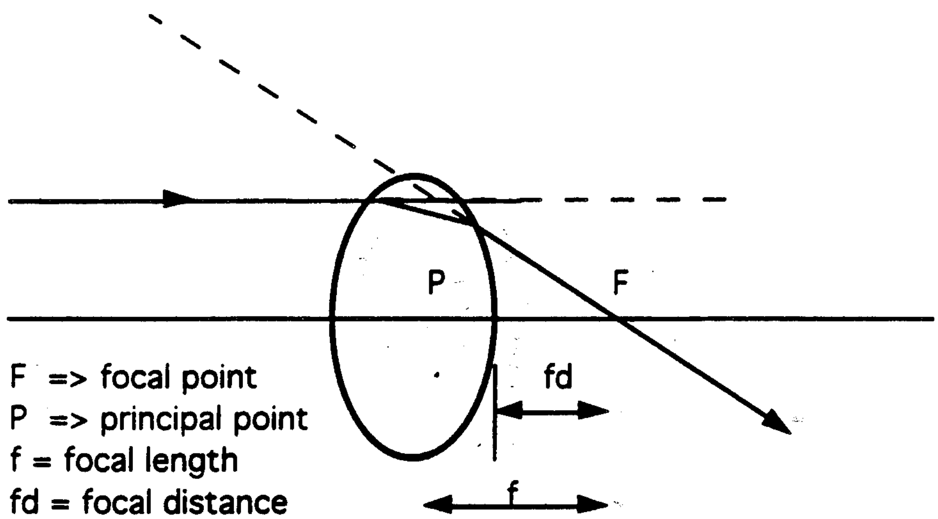

Figure 2-2. Location of the back principal point and the focal point of a lens.

Most lenses are designed using spherical surfaces on their component elements. These series of spherical surfaces do a miraculous job of transferring light from a point at the object (display) to a point at the image. However, lenses are not capable of producing an image point that is of as high a quality as the original object point. The reason for this degradation is due to either diffraction and/or aberrations in the optical system. If a lens is diffraction-limited, this means that the contribution of this degradation due to aberrations is much smaller than that due to diffraction. Typically, it is easier to make a lens diffraction limited by using more optical elements (surfaces) and by making the lens a higher F-number (F/No.). The F/No. of a lens is the ratio of its focal length to its diameter. Unfortunately, it is the lower F/No. lenses that are more desirable to have because of their increased light gathering capability. This produces a trade-off combination between lens complexity (size, weight, cost) and quality (resolution, light gathering).

Lenses are often named according to their function in an optical system. Figure 2-3 is a drawing of three of the four most commonly used names for lenses. The relay lens is used to 'relay' an image of an object (e.g. a display) to another location. Relay lenses are typically used when it is desirable to increase the distance between the object and where one wants the final image. An eyepiece lens is so named because it is the lens that is located closest to the eye. It serves as a simple magnifier to produce a virtual image from either a real image (as shown in Figure 2-3) or from an object (such as a display). The third lens in Figure 2-3 is a field lens which is located near or at the intermediate image plane. This lens is intended to collect more of the rays that come from the relay lens and get them into the eyepiece lens to increase the field-of-view of the system. The fourth lens, which is not shown, is an objective lens. The front lens on a night vision goggle (NVG) is an example of an objective lens. It produces an image of exterior objects onto the input of the image intensifier tube of the NVGs; hence the name objective lens. The relay lens shown in Figure 2-3, by using the display as an object to form an image for the eyepiece, is effectively, the objective of the optical system for viewing the display of, for example, a CRT. In a general sense, the image provided to the observer by the eyepiece is the system display or image display.

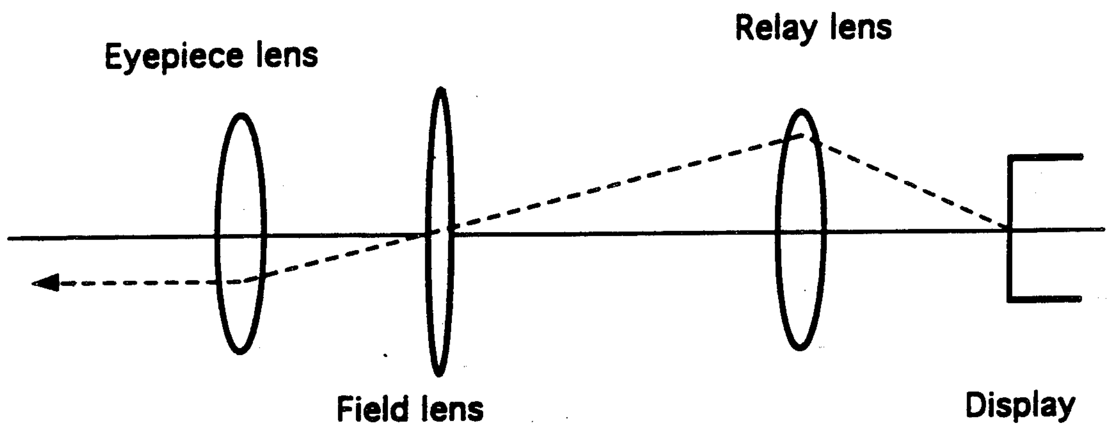

Figure 2-3. Lens names that are in common usage for HMDs.

One other element that is commonly found in HMDs is a combiner or beamsplitter. This element is so named because it combines (splits the light beam) the image of the HMD system onto the exterior scene. A combiner might also serve as part of the image-producing HMD system (an element with optical power), such as a parabolic visor.

Images can be either real or virtual. If you can put a piece of paper at the image plane and see the image formed on the paper, then it is a real image. If the above cannot be done then it is a virtual image. All HMDs produce a virtual image as an end product to be viewed by the observer. A simple magnifier lens used to enlarge objects or to view a CRT, etc. produces a virtual image.

For further information on optical systems refer to Hecht and Zajac (1975) or Klein (1970).

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SECTION 3

HELMET-MOUNTED DISPLAY (HMD) OPTICAL SYSTEMS

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BASIC HMD DESIGN DECISIONS

Before discussing the individual design parameters and their visual effects, one must first determine some very basic aspects of the HMD and its application. An HMD may be designed to be monocular, biocular, or binocular. Each approach has certain advantages and disadvantages. The display may be either monochrome or polychrome (multicolor), although most HMDs to date have been monochrome for technological reasons. Further, one must determine whether the HMD will be used for daytime or nighttime applications or both, which will have an impact on the determination of several of the optical parameters of the HMD. Finally, it needs to be determined if the HMD will be used for symbology only, imagery only, or both. Each of these requirements will affect the design options available in designing the HMD.

To properly describe these basic design decisions one would require a multi-dimensional trade-off matrix that would be difficult to present on two-dimensional paper. However, the following observations are presented on the advantages and disadvantages of each of the design choices without regard to interactions between them.

MONOCULAR HMD

The advantages of the monocular HMD are relatively low weight, low cost, and simplicity compared to the biocular or binocular HMD. The disadvantage is that, in general, the display is provided to only one eye resulting in a disparity between the two eyes that may cause some discomfort. It should be noted that a monocular HMD is the only HMD (other than night-vision goggles) currently in wide operational use (the IHADSS in the US Army Apache helicopter).

BIOCULAR HMD:

The biocular HMD presents a single image source to both eyes, thus eliminating the image disparity between the two eyes encountered in the monocular HMD (note: this does not eliminate the possibility of image misalignment between the two eyes; e.g. dipvergence). However, the optics and supporting mechanical parts required to produce the biocular HMD increase size and weight on the helmet which may result in increased discomfort and fatigue. Binocular systems are also much more expensive than monocular systems.

BINOCULAR HMD

The binocular HMD provides two entirely separate images to the two eyes, thus enabling the presentation of stereo imagery. However, this requires two independent image sources (which increases the weight and size on the helmet) and, to make use of the two display sources, requires two sensors on the aircraft to provide the two independent scenes.

SYMBOLOGY ONLY

If symbology only is displayed on the HMD, then the system needs to produce essentially only two 'gray shades', i.e., the symbol is either 'on' or 'off'. This means that the luminance requirements for the image source are less stringent compared to an imagery producing HMD. Additionally, the symbology is a relatively compatible process with respect to vision (Task et al., 1980) in that it appears as an overlay on the outside world scene (much like movie titles overlay a background scene in the introductory section of a movie).

IMAGERY ONLY

In order to display video imagery on the HMD, the display system must be able to produce several shades of gray. If the HMD uses a combiner, like a regular head-up display (HUD), then the combiner must have a low enough transmissivity to reduce the outside scene luminance sufficiently for the observer to see the HMD video image. However, the low transmissivity may make outside viewing difficult when the HMD is not in use and does reduce direct-vision acuity when scene illumination is low.

NIGHT ONLY

The advantage of using an HMD at night only is that it permits, via the sensor, scene visibility when otherwise impossible, and it is relatively easy to achieve the number of gray shades and luminance levels for good image quality. However, the disadvantage is one of logistics; requiring a different helmet for night versus day if it is also desirable to have daytime HMD capability.

DAY ONLY

This has the similar logistics problem as noted above, and would be more difficult to achieve the desired luminance levels, since one is competing against bright sunlight levels.

TABLE 1.
SUMMARY OF INITIAL HMD DESIGN DECISIONS

Item #	Options		
1.	Monocular	Biocular	Binocular
2.	Symbology	Imagery	Both
3.	Day use	Night use	Both
4.	Monochrome	Polychrome	
5.	Combiner	No combiner	

Table 1 is a summary listing of some of these initial HMD design decisions. There are other basic design decision trade-offs and considerations, but this should provide some insight into the entwined problems of desired operational capability and technology-limited design choices.

DESIGN PARAMETERS AND VISUAL EFFECTS

There are a number of design parameters (in addition to the design choices discussed above) that must be considered when specifying or producing an HMD. The purpose of this section is to discuss some of these parameters and how they interact with human visual capability. These are presented more or less in order of importance; although all are important and have an effect on visual performance. Table 2 is a summary listing of these parameters.

TABLE 2
HMD DESIGN AND VISION PARAMETERS

DESIGN PARAMETERS	VISION PARAMETERS
Field-of-view	Visual field
Image quality	Visual acuity
Exit pupil size	Eye pupil diameter
Eye relief	Eyeglasses
Image location (focus)	Accommodation
Field curvature	•
Luminance level	Brightness
Luminance uniformity	•
Beamsplitter ratio	•
Distortion	Image perception
Binocular parameters	Binocular effects
Color	Color contrast
Fixed pattern noise	Masking/distraction

The HMD design parameters in Table 2. are positioned across from the corresponding vision parameter affected. However, it should be noted that this correspondence is approximate, and that there is considerable interaction between some of these parameters. Most of the HMD design parameters listed in Table 2. are discussed in terms of their effect on vision.

FIELD-OF-VIEW

Probably the first parameter that most people are concerned with in an HMD is the field-of-view (FOV). The FOV is the angular subtense of the virtual image displayed to the wearer. This is typically expressed in degrees for both the vertical and horizontal dimensions, or for the diameter of the FOV, if it is circular.

In general, the size and weight of the HMD increase as the FOV is increased which is a key factor in limiting the FOV of HMDs. Another practical problem is the trade-off with resolution (image quality). An image source (e.g., a cathode-ray tube or CRT) has a finite number of picture elements (pixels). As the FOV is increased, these pixels are spread over a larger angular expanse, resulting in a larger angular subtense per pixel which corresponds to a lower angular resolution to the observer. (Note: this is an oversimplification of this trade-off, since image quality is more complex than the concept of pixels implies, but the general direction of the trade-off is the same: larger FOV means lower visual resolution).

HMDs have been built with FOVs ranging from a few degrees up to 80 degrees and more. How much FOV is required depends very heavily on the specific application. The first helmet-mounted sight (HMS) system deployed by the United States military had very limited symbology on the HMD. This system, called the Visual Target Acquisition System (VTAS) had a display consisting of two concentric rings (aiming reticle) of 10 mrads and 50 mrads with four other discrete indicator lights outside of these aiming reticles. The entire field of view was approximately 5 degrees (Ferrin, 1973). At the other extreme, HMDs have been built for laboratory research purposes with FOVs as large as 120 degrees wide by 60 degrees high (Wells et. al., 1989). Typical FOVs for operational use are in the range of 20 degrees to 40 degrees (Task et. al., 1980).

The visual parameter that corresponds to the HMD FOV is the human eye's angular visual capability, which is approximately 200 degrees horizontally and 120 degrees vertically (Wells et al., 1989). However, this is somewhat misleading, since the visual capability over this range is quite varied. Only the central 3-5 degrees provides high-acuity vision; the visual acuity drops off quite rapidly outside of this area. This means that, for moderate FOV HMDs, much of the resolved details on the display are not being used by the visual system; but the 'extra' FOV is important for providing peripheral vision information.

The total HMD FOV can be made larger by making the FOV of each ocular of a binocular HMD only partially overlap. The visual effects of partial overlap may outweigh the value of the extended horizontal FOV if the overlap is too little. (Melzer and Moffitt, 1991) At least one study suggests that there is little performance difference between 100 percent overlap and 80 percent overlap for visual recognition performance (Landau, 1990) implying that an 80 percent overlap binocular HMD may be a good compromise between the need for larger FOV and reduced visual performance in the non-overlapped areas.

IMAGE QUALITY

Image quality is a complex subject that involves several other parameters (Task, 1979). Probably the key indicator of image quality is the modulation transfer function (MTF) of the display, which describes how much contrast is available as a function of spatial frequency (detail). Two parameters related to the MTF are gray-shades (contrast) and resolution (maximum spatial frequency that can be seen or 'resolved'). For simplicity, the resolution of a display relates to the number of pixels. As noted earlier, the resolution tends to decrease as FOV increases, which implies that image quality also decreases with increasing FOV; another trade-off of two desirable attributes.

If the HMD is to be used for day-time imagery viewing and uses a combiner (to combine the HMD image/symbology with the outside scene), then image quality and the combiner transmissivity form another trade-off pair. In order to see the HMD image without degrading effects of the outside scene, the combiner transmissivity needs to be low (and/or the HMD image generator needs to produce a high luminance level). However, a low combiner transmissivity results in reduced visibility of the outside scene when the HMD is not in use.

The visual parameter corresponding to image quality (resolution and contrast) is visual acuity. Normal visual acuity for the human eye for highly luminous objects is approximately one minute of arc, depending on the contrast and shape of the object. Thus, if one were to match the display image quality to the human eye, a first order design might result in a pixel on the display subtending an angle of one minute of arc.

For an image source consisting of 500 by 500 pixels, this would mean a width or height angular subtense of the entire display of 500 minutes of arc, or 500/60 = 8.3 degrees. While this HMD might result in good image quality to the human eye, it would be an extremely small display. Most HMDs provide a FOV that results in an angular resolution much larger than the one minute of arc suggested by human visual capability.

EXIT PUPIL

Most, but not all, HMDs have a real exit pupil. The exit pupil is the image of the stop of the optical system. An exit pupil is formed as a result of using relay optics to produce an intermediate image plane which is then viewed by an eyepiece lens. This is in contrast to a simple magnifier optical system which uses a single lens system (no intermediate image) and therefore does not produce a real exit pupil. In a darkened room, with the HMD activated, the exit pupil can be observed by placing a piece of white paper near the designed eye position. For most systems a circular spot of light will be observed imaged on the paper. As the paper is moved closer to and further away from the optical system there is a point at which the disc of light has a minimum diameter with sharply defined edges. The diameter of this disk of light is the diameter of the exit pupil of the system (Self, 1973).

When the eye pupil is fully within the exit pupil of the HMD, then the entire FOV is observed; if the eye pupil is only partially in the exit pupil (and the exit pupil is unvignetted), then the observer will still see the entire FOV, but it will be reduced in brightness. This can be particularly disconcerting for HMDs used in high performance aircraft, because the pilot may not know whether he is starting to lose the exit pupil or if he is starting to lose consciousness from high acceleration maneuvers. Once the eye pupil is outside the truncated cone of the forming the exit pupil, then none of the HMD FOV can be seen. It should also be noted that the HMD FOV may become vignetted (lose part of the image) if the eye pupil is too close to or too far away from the exit pupil.

From a visual capability standpoint, it is important for the exit pupil to be as large as possible to ensure that the eye pupil will remain within it to permit viewing of the HMD. However, large exit pupils typically come only at the expense of greater size of optics and weight on the head. In addition, if the FOV is very large, then the eye must rotate to view the edge of the display. Since the eye rotates about a point within the eye, the eye pupil moves within the HMD exit pupil. If the HMD exit pupil is not large enough, then it is possible for the entire display to disappear every time the observe tries to move his eyes to view the edge of the display. Exit-pupil-forming optical systems also increase the difficulty of making accurate adjustments for binocular or biocular HMDs, in that each eye pupil should be centered in each exit pupil of the HMD.

Exit pupil diameters of HMDs that have been built range from a few millimeters to as much as 20 millimeters, with typical values of 10 to 15 mm diameter (Task et al., 1980).

EYE RELIEF

The optical eye relief is the distance from the exit pupil to the nearest part of the HMD optical system. If the HMD is non-pupil-forming then the eye relief is the distance from the HMD optical system to the farthest back position of the eye where the eye can still see the entire FOV of the HMD. Since the exit pupil is within the eye for proper use, eye clearance is a little less than eye

As with so many other HMD parameters, larger eye relief usually means larger and heavier optics. The reason for having a large eye relief is to allow the use of eyeglasses with the HMD (Self, 1973; Task et al., 1980).

IMAGE LOCATION AND FIELD CURVATURE

The HMD produces a virtual image for viewing by the observer. Typically, the HMD is designed to produce this image at optical infinity; a so-called collimated image. The reason for this is to place the HMD image at the same optical distance as the outside world, much like a head-up display (HUD) in a fighter aircraft. For symbology-only HMDs, this places the symbology and the externally observed scene in the same optical plane, thus eliminating parallax between the symbology and the scene. For night operations or imagery on the HMD, there typically is no external scene to combine with the HMD image, and, therefore, the need for collimation is not present.

Virtual images may also have field curvature, which means that not all of the image is at the same optical distance. The center of the field may be at infinity, but the edge of the field may be optically only a few meters away.

The effect of the image location and curvature is that the eye lens must focus on the optical plane in which the image is located. For young eyes which are properly corrected and retain a good accommodative range (they can focus at 10 inches to infinity), mild field curvature is not a problem. However, for older eyes which no longer have a large accommodative range, it may not be possible to have the entire HMD FOV in good focus as the observer looks through-out the FOV. If the HMD permits focusing adjustment (like many night-vision goggles), then it is possible to bring the image location into a distance at which the eyes can focus (for myopes), or out to a distance where focus can be achieved (hyperopes).

For night operations, it makes sense to have the HMD image focused at the same distance as the aircraft panel instruments to minimize the eye-focus time required to visually switch between looking at the HMD and looking at panel-mounted flight instruments.

LUMINANCE LEVEL

The luminance of the HMD image depends both on the luminance of the image source and the transmission efficiency of the optical system (note: it does NOT depend on the amount of magnification since it produces a virtual image). For HMDs that use a combiner, the HMD image luminance level depends very heavily on the combiner (beamsplitter) reflectance and transmittance coefficients.

Brightness is the visual sensation or perception that corresponds to (correlates with) luminance. The luminance level has a significant effect on the pupil diameter of the eye; a higher light level means a smaller pupil diameter and vice versa. The visual acuity of the human eye also varies with eye pupil diameter (Farrell & Booth, 1984). However, for night HMD applications the image display luminance must be kept reasonably low to match cockpit lighting levels. Thus, the resolution observed by the eye on the HMD may well be lower for night HMD use than for day use.

BINOCULAR PARAMETERS

There are several other parameters that become important if the HMD is binocular. These include inter-pupillary distance (IPD-the distance between the exit

pupil centers of the two oculars), image alignment between the two oculars, luminance balance, fit stability, and others.

There are several undesirable visual effects that may occur in binocular HMDs. These include binocular disparity (retinal rivalry) due to luminance imbalance, image misalignment, accommodation differences, and/or differential distortion. When binocular disparity is sufficiently severe, the observer will see double images or may suppress one of the two disparate images. A more insidious problem is when the binocular disparity is not large enough to cause a loss of image fusion but is enough to result in 'eye strain' or visual fatigue. This can lead to visual fatigue, headache, or nausea during extended use, but may not show any effects for short term use.

There have been some efforts to define the limits for these types of parameters (Self, 1973 and 1986; Landau, 1990).

MISCELLANEOUS

As evident from Table 2, there are many other parameters that affect the overall acceptability and performance of an HMD. Two of the key parameters that are usually acknowledged, but that really don't receive the attention they should, are size and weight. For many operational applications, if the HMD is unacceptable from the standpoint of size and/or weight, then it really doesn't matter how wonderful the rest of the performance characteristics are. Additionally, two other aspects that have received relatively little attention are comfort and fit. These are also exceedingly important for both commercial and military acceptance of HMDs (and, unfortunately, also exceedingly difficult to accomplish and measure).

OPTICAL SYSTEM DESIGN TRADE-OFFS FOR THE SIMPLE MAGNIFIER

There are two broad classes of optical systems that have been adopted for use in HMDs. The more complicated of the two uses a relay optical system to produce an intermediate image of the display. This intermediate image is then viewed by the operator through an eyepiece optical component (lens or curved mirror). This type of system creates a real exit-pupil. The other HMD optical system is a simple magnifier. This is a single lens/mirror system which produces a virtual image of the display directly, without use of relay optics.

The purpose of this section is to present several equations that govern the design parameter trade-offs for simple magnifier systems. Graphs produced from these equations provide a visual demonstration of these trade-offs. Figure 3-1 is the basic optical arrangement for a simple magnifier display with the display set at the focal point of the lens to produce a virtual image at infinity. The FOV, display size (s), and the focal length of the lens (f) are related by equation (1).

$$FOV = 2 * \arctan(s/(2*f)) \qquad (1)$$

Where:

- FOV = angular field-of-view
- s = size of display
- f = focal length of lens

Equation (1) was derived assuming that the display was located at the focal point of the lens to produce the virtual image at infinity. However, it is not always desirable to set the virtual image distance for infinity. Specifically, it is often desirable to make the eyepiece adjustable to change the distance from the display to the rear principle plane

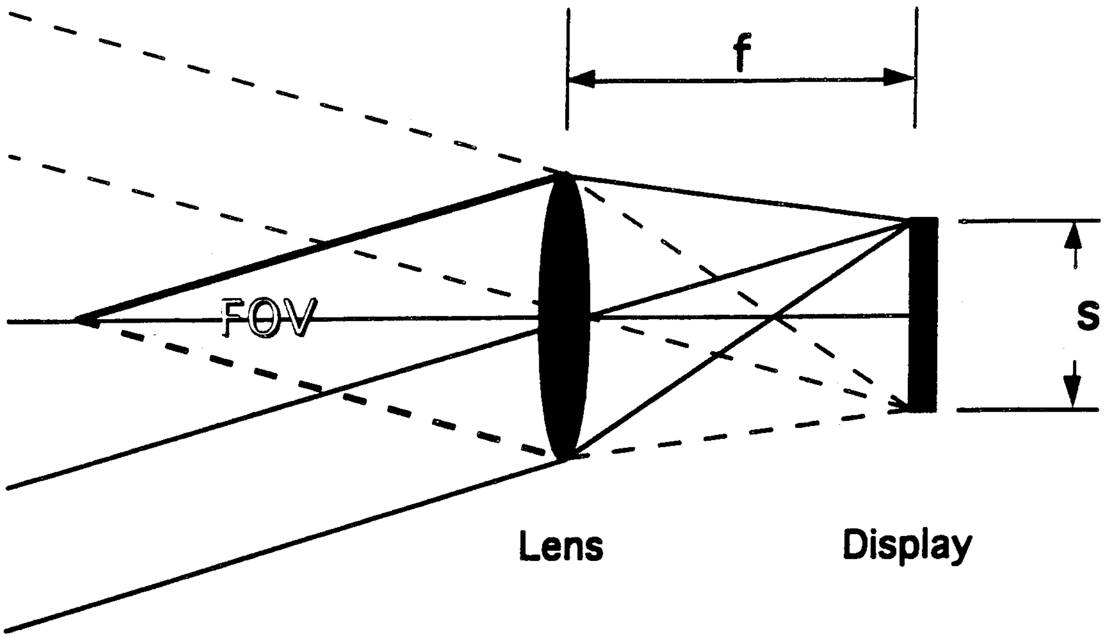

Figure 3-1. Simple magnifier HMD geometry to produce virtual image at infinity.

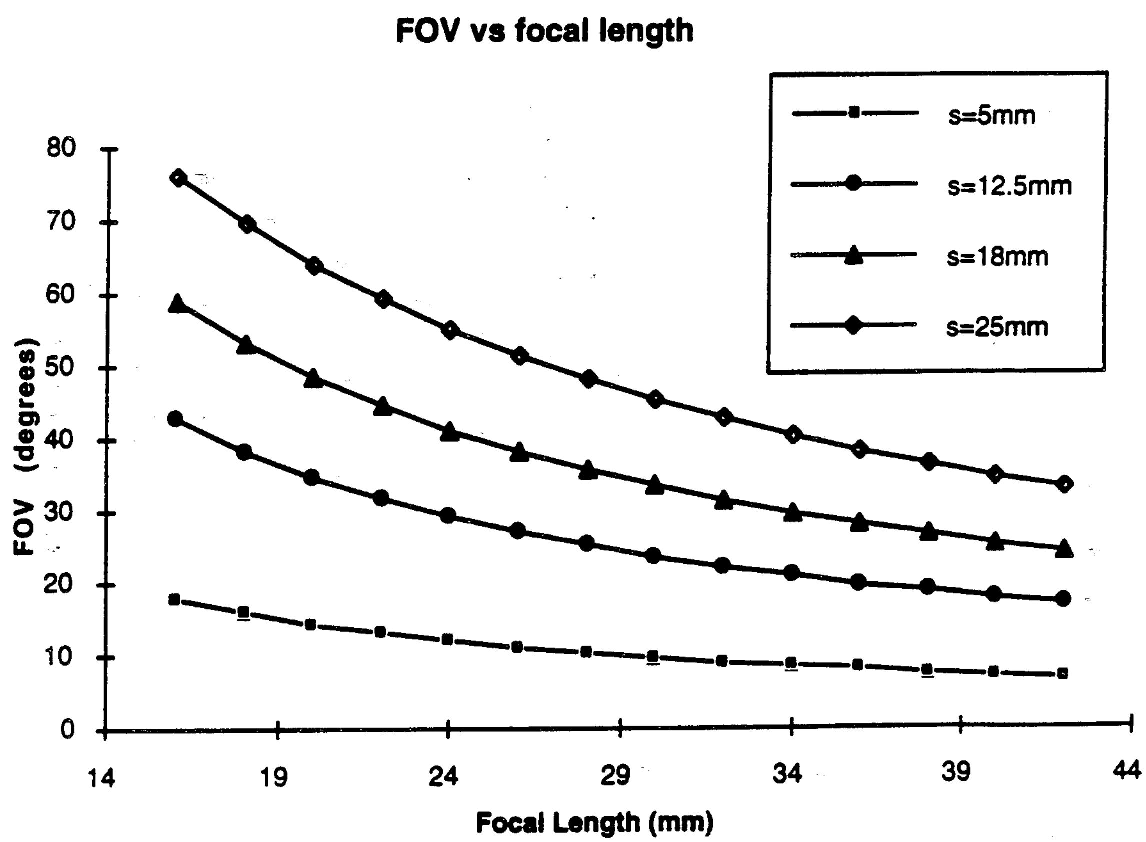

Figure 3-2. Graphical representation of equation (1) showing the trade-offs between display size, lens focal length and field-of-view.

of the eyepiece, so that people who are near-sighted or far-sighted can focus the display to compensate for their eyesight. Equation (2) describes the effect of display distance on the location of the virtual imagefrom the lens equation $1/d-1/I_O=1/F$, I_O-$dF/(F-d)$=lens-to-image distance. Eye-to-image distance-I_O+eye-to-lens distance= for a simple .

$$I = \frac{d\ f}{(f-d)} + le \qquad (2)$$

Where:

I = Image distance from the eye
d = distance from lens to display
f = focal length of lens
le = eye relief distance (eye to lens)

Note that, if d=f, then the denominator is zero and the image distance 'I' goes to infinity. If 'd' is less than 'f,' then the system will produce a virtual image located a finite distance from the observer. This condition will accommodate observers who are near-sighted. If 'd' is larger than 'f,' then the image distance 'I' is actually negative and, strictly speaking, does not produce a virtual image in front of the eye. However, this condition is what permits the system to compensate for far-sighted observers. Figure 3-3 is a set of graphs generated using this equation for several focal length lenses using an eye relief distance of 25mm.

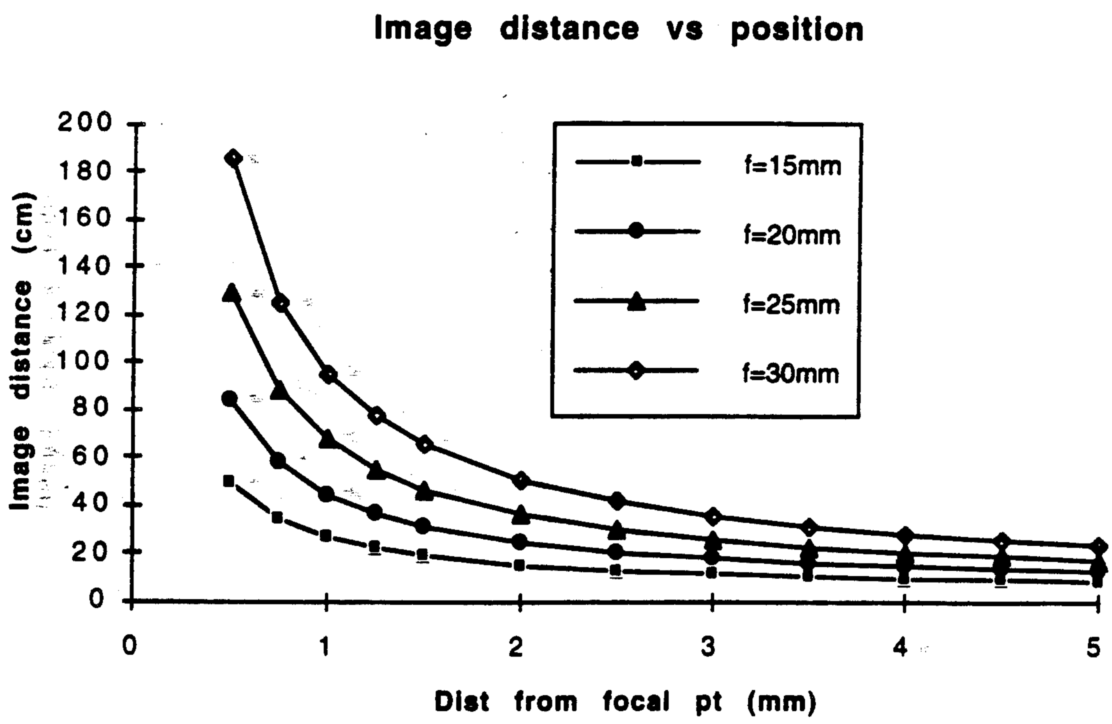

Figure 3-3. Effect of focal length and image source (display) position on virtual image distance from the eye. The horizontal axis is the distance from the focal point of the lens to the display surface (i.e., (f-d) from equation 2). The eye relief 'le' used to produce these graphs was 25mm.

If the display is not positioned at the focal point of the lens, the field-of-view, as calculated in equation (1), may be changed. Equation (3) is a more general equation describing the field-of-view obtained as a function of display distance, eye relief, image size, and lens focal length.

$$\mathrm{FOV} = 2 \quad \arctan\left\{\frac{s}{2\,(d + le((f-d)/f)}\right\} \tag{3}$$

Where:
FOV = field-of-view
s = display size
d = distance from lens back principle plane to display
le = distance from eye to front principle plane of lens
f = focal length of lens

Note that, in equation (3), if the distance 'd' is set equal to 'f,' then this equation reduces to equation (1) independent of what the eye relief 'le' is. A further note of interest is that if the eye relief 'le' is set equal to the focal length 'f' then the equation also reduces to equation (1) independent of what 'd' is. This second effect is quite interesting, because it means that it is possible to set an eye relief distance such that the FOV will not change as one adjusts the eyepiece lens to compensate for near-sighted and far-sighted observers.

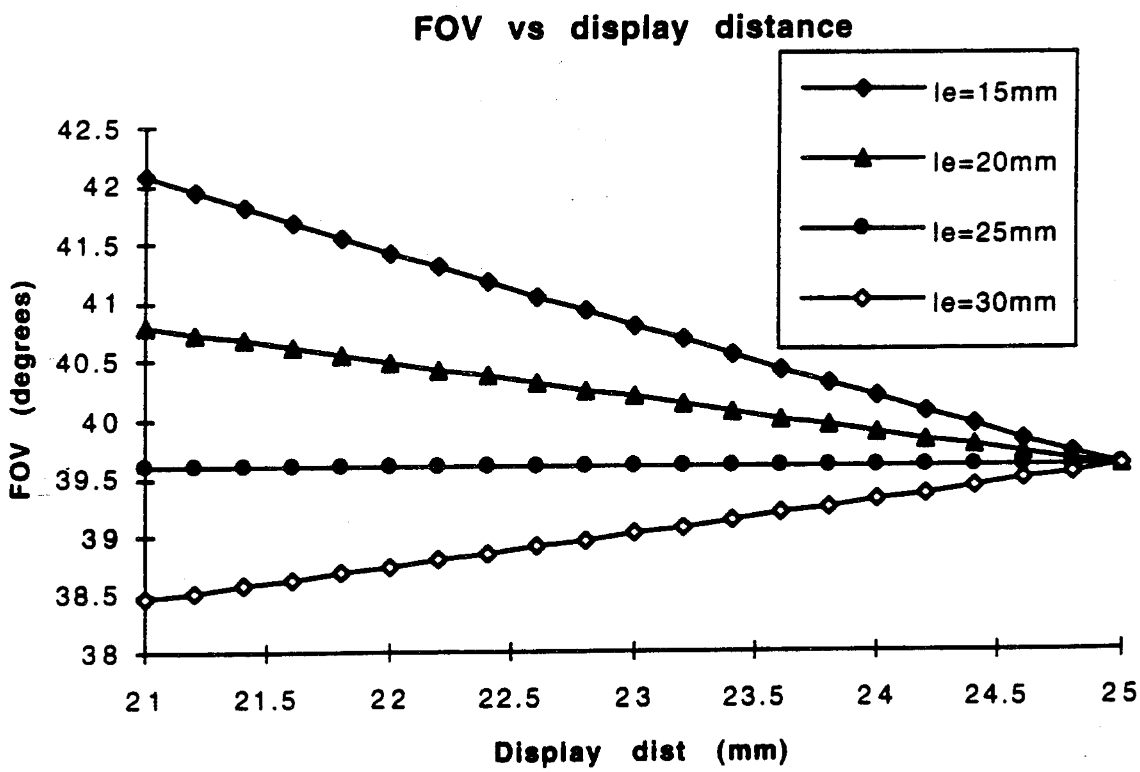

Figure 3-4. Effect of display distance and eye relief on apparent field-of-view. Graphs were generated using equation (3) with a lens focal length of 25mm and a display size of

18mm. Note that, when the display distance equals the focal length (25mm in this case), the field-of-view is the same regardless of eye relief. Also, if the eye relief is equal to the focal length, then the field-of-view remains constant independent of the display distance (the 'le=25mm' line).

Figure 3-4 is a graph of the variation of FOV with focal length and display distance from the principle plane. Equation (3) assumes that the lens diameter is sufficiently large as to not limit the FOV (the effect of lens diameter on FOV is discussed later). Although the variation in FOV due to the distance 'd' and 'le' may not be very much, they can have an effect on viewing a binocular HMD that has the two oculars adjusted for different image distances. This will produce a size difference between the two images unless the eye relief distance is set at the focal length of the lens. The graphs in figure 3-4 were generated using a lens focal length of 25mm and a display size of 18mm.

As stated earlier, a simple magnifier lens system does not have a real exit pupil. However, there is a restriction on where the eye must be in order to see the entire FOV without vignetting. Figure 3-5 is a sketch showing the relationship between the lens diameter, lens focal length, display size, eye relief, and the eye motion box which has, on many occasions, been referred to as an 'exit pupil.'

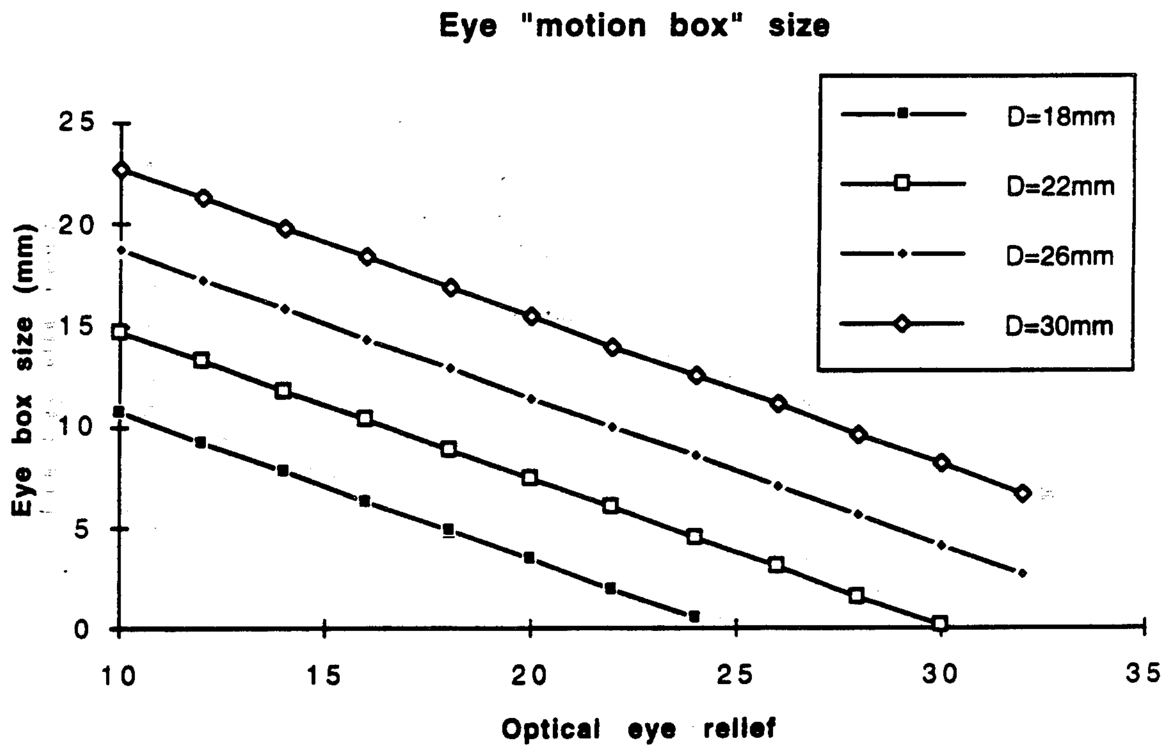

Figure 3-5. Relationship between display size, eye relief, lens diameter, lens focal length and eye motion box ('exit pupil'). These graphs were derived using a 25mm focal length lens with an 18mm display size and a FOV of 4 degrees. Note that this is for the case where the display is located at the rear focal point of the lens.

Using simple geometry, it is possible to derive equation (4) which mathematically describes this relationship.

$$E = D - \frac{le\ s}{f} \tag{4}$$

Where:

E	=	eye motion box ('exit pupil') = Exit pupil diamter
D	=	lens diameter
s	=	display size
le	=	eye relief distance
f	=	focal length of lens

Equations 1 through 3 implicitly assumed that the lens diameter was sufficiently large so as not to limit the available FOV. Equation 4 describes the relationship between lens focal length, lens diameter, eye relief, display size, and 'eye motion box' size. At some optical eye relief distance, the eye motion box size is the same as the entrance pupil to the eye. This is the maximum optical eye relief possible without causing vignetting at the edge of the FOV. It should also be noted that the actual physical eye clearance will be somewhat less than this value since the entrance pupil of the eye is located about 3mm behind the corneal surface, and since the rear principle plane of the eyepiece lens is typically not at the back glass surface of the lens system.

The previously-discussed equations assumed that the eye relief and lens diameter were such that they did not limit the field-of-view of the system. This, obviously, is not always the case. For a simple magnifier optical system, the FOV will be vignetted (clipped) if the observer's eye is too far from the lens. The relationship between this distance (eye to lens) can be related to the FOV remaining. When the eye is far enough from the lens that the entire FOV is not visible, then there is an ambiguity in determining what is the instaneous FOV. For points that are near the edge of the field, it is possible to define the edge of the FOV as that angle at which there is no vignetting of the light from the edge, 50 percent vignetting, or just at the 100 percent vignetting. Figure 3-6 is a drawing of the rays coming from a lens that represent the angles corresponding to 0percent, 50 percent, and 100 percent vignetting. Visually, what one sees is that the edge of the FOV is 'fuzzy'; where this fuzziness begins is the field angle that corresponds to 0 prcent vignetting, approximately in the middle of it is the 50 percent vignetting angle and at the very edge of the visible field is the 100 percent point.

There are, therefore, six equations that can be used to determine the FOV based on the eye to lens distance and the level of vignetting that one wishes to use to define the FOV. These are listed as equations 5 through 10. Figure 3-7 is a graph of the apparent FOV as a function of eye distance for the three vignetting cases (0 percent, 50 percent, and 100 percent). The graphs were produced using a focal length of 25mm, a display size of 18mm and a lens diameter of 18mm.

Case 1 - 0% vignetting:

For $le < (f(D-e)/s)$ $\quad$ $FOV = 2 \arctan(s/(2\ f))$ $\quad$ **(5)**

For $le > (f(D-e)/s)$ $\quad$ $FOV = 2 \arctan((D-e)/(2\ le))$ $\quad$ **(6)**

Case 2 - 50% vignetting:

For le < (f*D)/s	FOV = 2 arctan(s/(2 f))	**(7)**
For le > (f*D)/s	FOV = 2 arctan(D/(2 le))	**(8)**

Case 3 - 100% vignetting:

For le < (f(D+e)/s)	FOV = 2 arctan(s/(2 f))	**(9)**
For le > (f(D+e)/s)	FOV = 2 arctan((D+e)/(2 le))	**(10)**

Where:

le =	eye relief	FOV =	field-of-view
D =	lens diameter	e =	eye pupil diameter
s =	display size	f =	lens focal length

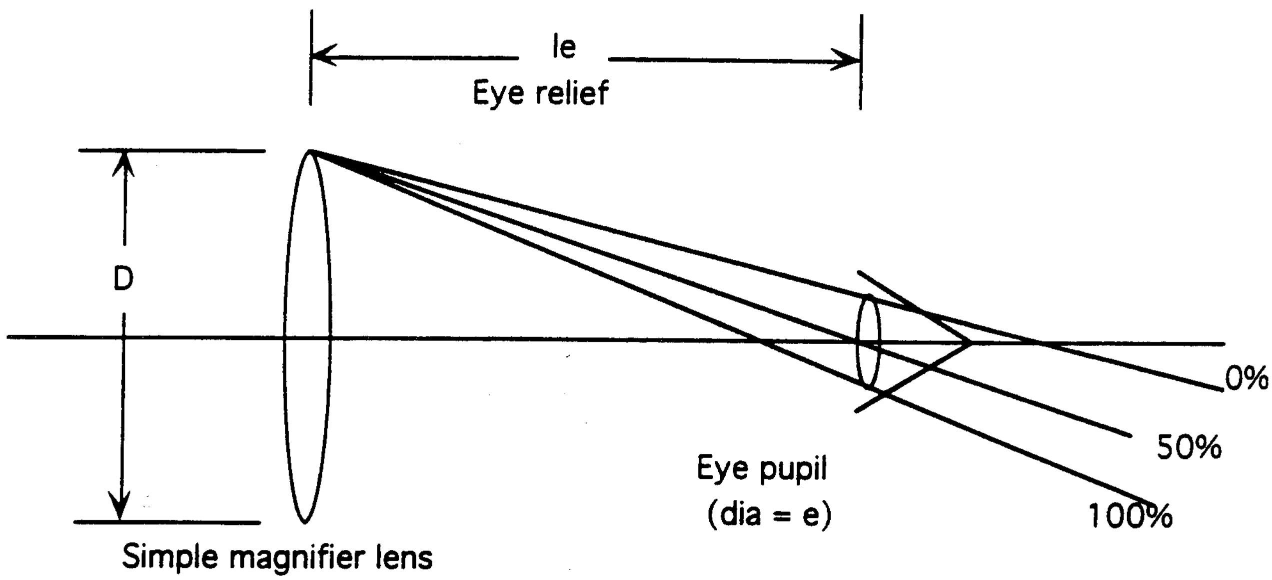

Figure 3-6. Drawing showing the rim rays that correspond to 0%, 50% and 100% vignetting for determining apparent field-of-view.

For a given display size, one can obtain a larger FOV by using a shorter focal length lens. As explained in the preceding material, this results in a shorter eye relief distance. It also will result in a reduced visual resolution. The display limiting resolution can be expressed in cycles/mm, which corresponds to the highest spatial frequency pattern that can be seen (resolved) on the display. When viewed through the simple magnifier optical system, this is then converted to cycles/degree by using equation 11. Since the display size is fixed and its linear resolution (cycles/mm) is fixed, then the total number of picture elements (pixels) is also fixed. If one produces a larger FOV by reducing the focal length of the lens then the same fixed number of pixels must be spread over a larger angular area which reduces the apparent visual resolution. By combining equations (1) and (11), it is possible to generate an equation which describes this trade-off between FOV and visual acuity (angular resolution).

Equation (12) is the result. Note that equation (12) was derived for the limited case where the display is at the focal point of the lens.

$$\mathrm{Vres} = \frac{1}{\arctan\left(1/(f\ \mathrm{Lres})\right)} \qquad (11)$$

$$\mathrm{FOV} = 2 \arctan[((s\ \mathrm{Lres})/2) \tan(1/\mathrm{Vres})] \qquad (12)$$

Where:

Vres = visual angular resolution (cycles/degree)
Lres = linear display resolution (cycles/mm)
f = focal length of lens (mm)
s = size of display (mm)
FOV = field-of-view (degrees)

Figure 3-7 is a graph of apparent FOV for a simple magnification as a function of eye-to-eyepiece distance for 0 percent, 50 percent and 100 percent vignetting.

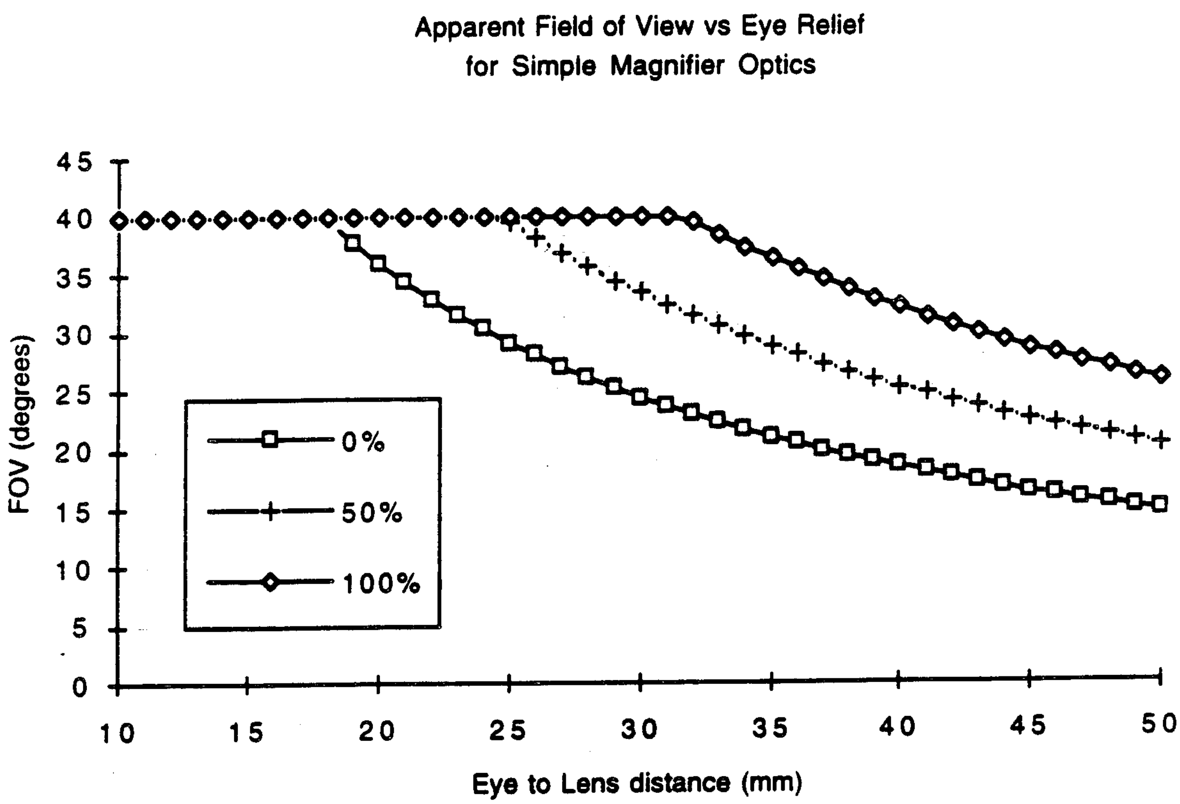

Figure 3-7. Apparent field-of-view of eye distance from the lens for a system with f-25mm, D-18mm, and e-5mm. Graphics generated using equations 5 through 10.

Figure 3-8 is a graphic representation of equation 12 showing the trade-off between HMD FOV and visual angular resolution for several display linear resolutions.

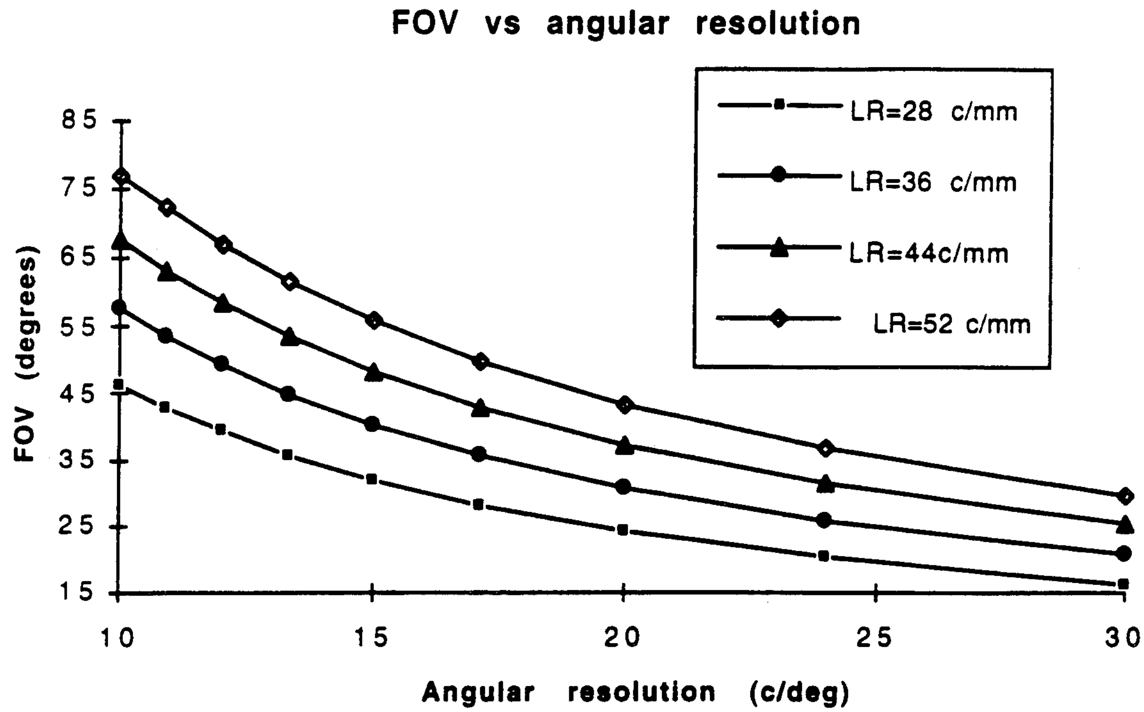

Figure 3-8. Field-of-view versus resolution for several display linear resolutions. These curves were generated using equation 12 with the lens focal length of 25mm, display size of 18mm and the display located at the focal point of the lens. These curves assume that the eye is close enough to the lens that the lens diameter does not become a limiting factor.

In order to get a better feel for the trade-off between FOV and visual resolution, it is possible to convert the visual angular resolution values into Snellen acuity (which may be more familiar to most people). Equation 13 converts visual angular resolution in cycles/degree to Snellen acuity by using the assumption that 20/20 visual acuity is equivalent to 30 cycles/degree visual angular resolution.

$$Vres = \frac{600}{xx} \tag{13}$$

Where:

xx = Snellen acuity (as in 20/xx)
Vres = visual angular resolution (cycles/degree)

If this is substituted into equation 12, one obtains:

$$FOV = 2 \arctan\{((s\ Lres)/2) \tan(xx/600)\} \tag{14}$$

Where:

xx	=	Snellen acuity (as in 20/xx)
Lres	=	linear display resolution (cycles/mm)
f	=	focal length of lens (mm)
s	=	size of display (mm)
FOV	=	field-of-view (degrees)

Figure 3-9 was produced using equation 14 and the same data as was used to generate figure 3-8. The larger visual acuity numbers correspond to poorer vision/resolution.

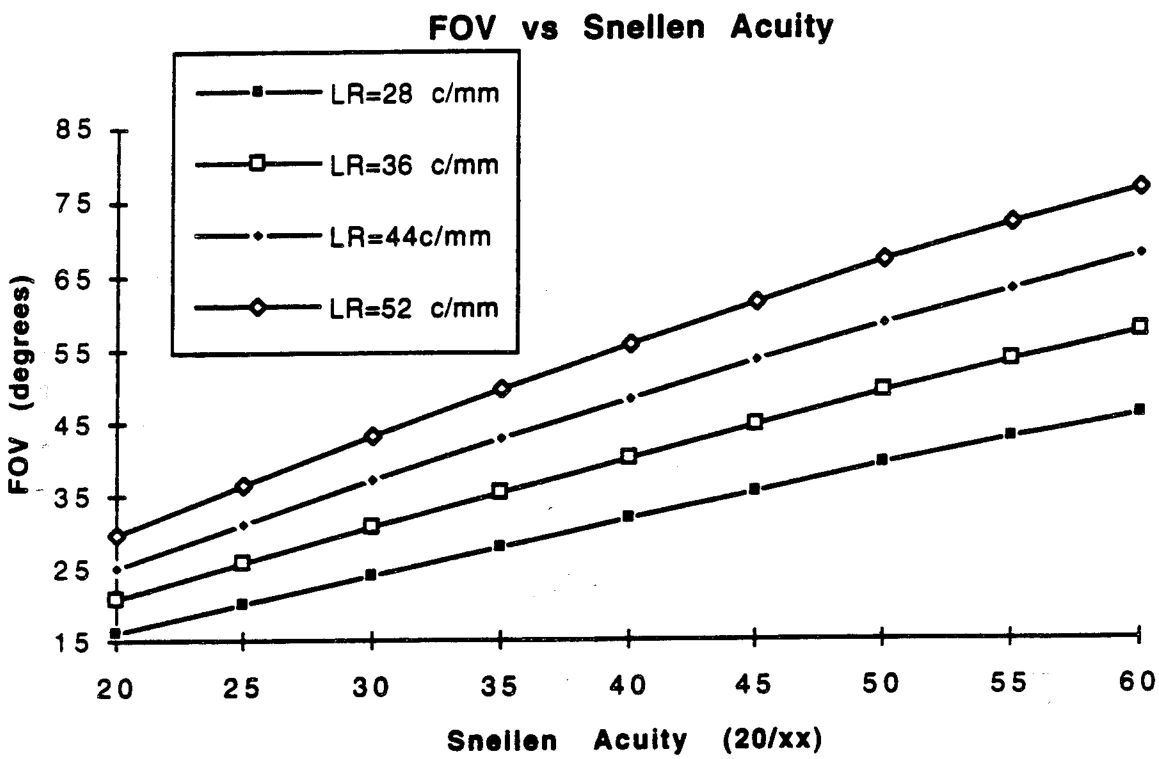

Figure 3-9. Field-of-view versus Snellen acuity for several display linear resolutions. These were generated using equation 14 with focal length of 25mm, display size of 18mm and the display at the lens focal length. It is assumed that the eye is close enough to the lens that the lens diameter does not limit the FOV.

Table 3-3.
Conversion table to change between Snellen acuity and visual angular resolution stated in either cycles per milliradian or cycles per degree.

Vres c/mrad	Vres c/deg	Snellen 20/xx	Snellen 20/xx	Vres c/mrad	Vres c/deg	Vres c/deg	Snellen 20/xx	Vres c/mrad
0.50	8.7	69	60	0.57	10.0	10.0	60	0.57
0.52	9.1	66	59	0.58	10.2	10.5	57	0.60
0.54	9.4	64	58	0.59	10.3	11.0	55	0.63
0.56	9.8	61	57	0.60	10.5	11.5	52	0.66
0.58	10.1	59	56	0.61	10.7	12.0	50	0.69
0.60	10.5	57	55	0.63	10.9	12.5	48	0.72
0.62	10.8	55	54	0.64	11.1	13.0	46	0.74
0.64	11.2	54	53	0.65	11.3	13.5	44	0.77
0.66	11.5	52	52	0.66	11.5	14.0	43	0.80
0.68	11.9	51	51	0.67	11.8	14.5	41	0.83
0.70	12.2	49	50	0.69	12.0	15.0	40	0.86
0.72	12.6	48	49	0.70	12.2	15.5	39	0.89
0.74	12.9	46	48	0.72	12.5	16.0	38	0.92
0.76	13.3	45	47	0.73	12.8	16.5	36	0.95
0.78	13.6	44	46	0.75	13.0	17.0	35	0.97
0.80	14.0	43	45	0.76	13.3	17.5	34	1.00
0.82	14.3	42	44	0.78	13.6	18.0	33	1.03
0.84	14.7	41	43	0.80	14.0	18.5	32	1.06
0.86	15.0	40	42	0.82	14.3	19.0	32	1.09
0.88	15.4	39	41	0.84	14.6	19.5	31	1.12
0.90	15.7	38	40	0.86	15.0	20.0	30	1.15
0.92	16.1	37	39	0.88	15.4	20.5	29	1.17
0.94	16.4	37	38	0.90	15.8	21.0	29	1.20
0.96	16.8	36	37	0.93	16.2	21.5	28	1.23
0.98	17.1	35	36	0.95	16.7	22.0	27	1.26
1.00	17.5	34	35	0.98	17.1	22.5	27	1.29
1.02	17.8	34	34	1.01	17.6	23.0	26	1.32
1.04	18.2	33	33	1.04	18.2	23.5	26	1.35
1.06	18.5	32	32	1.07	18.8	24.0	25	1.38
1.08	18.8	32	31	1.11	19.4	24.5	24	1.40
1.10	19.2	31	30	1.15	20.0	25.0	24	1.43
1.12	19.5	31	29	1.19	20.7	25.5	24	1.46
1.14	19.9	30	28	1.23	21.4	26.0	23	1.49
1.16	20.2	30	27	1.27	22.2	26.5	23	1.52
1.18	20.6	29	26	1.32	23.1	27.0	22	1.55
1.20	20.9	29	25	1.38	24.0	27.5	22	1.58
1.22	21.3	28	24	1.43	25.0	28.0	21	1.60
1.24	21.6	28	23	1.49	26.1	28.5	21	1.63
1.26	22.0	27	22	1.56	27.3	29.0	21	1.66
1.28	22.3	27	21	1.64	28.6	29.5	20	1.69
1.30	22.7	26	20	1.72	30.0	30.0	20	1.72

Resolution values for HMDs and night vision goggles (NVGs) may be expressed in cycles/milliradian, cycles/degree, or Snellen acuity. Table 3-3 is a summary of conversions between these different units. It is divided into three sets of three columns each. The first column in each set was used to generate the values shown in

the other two columns of the set. The purpose of this table is to permit easy conversion from one type of unit to another. To convert from one unit to another, go to the set of columns that has the unit you want to convert FROM in the first column in the set. Then move down the column until you see the value that you are interested in and read across the row within that set to find the value converted to the other units. For example, if you knew a system had a visual resolution of 0.76 cycles/milliradian you would go to the first set of three columns, since its first column is in units of cycles/mrad. If you wished to convert this to Snellen acuity, you would look down the first column until you saw the 0.76 cycles/mrad then look across to the last column in the set (the third column in Table 1) and see that this corresponds to a Snellen acuity of 20/45.

This section has investigated a number of trade-offs that must be considered for a simple magnifier type of virtual display. In general, these same types of trade-offs hold for more complex virtual displays involving relay lenses and real exit pupils. When using any of the equations listed in this section you are cautioned to make sure that the assumptions under which the particular equation was derived are met.

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SECTION 4

HELMET-MOUNTED DISPLAY (HMD) IMAGE SOURCE, WIRING HARNESS, and DRIVE ELECTRONICS

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This section discusses the functionality and technology associated with the selection and use of the HMD image source, the design of the display electronics that drives the image source, and the signal conduit that acts as the electrical interface between the machine and the helmet mounted system.

IMAGE SOURCES

INTRODUCTION

As may be seen from Figure 4-1, there are a large number of candidate image sources that might be used in displays. Each candidate is useful in one or more respect, but consideration of size, weight, cost, resolution and brightness still make the miniature cathode ray tube the most popular candidate. While this seems unlikely to change soon for military aircraft, special circumstances make others attractive.

Miniaturization of the display and its support equipment have made vacuum fluorescent displays attractive for low brightness conditions, such as in forward looking infrared (FLIR)-IR-to-visible image-conversion.

Liquid crystals are important because they operate with low voltage, a strong safety feature, and draw very low amounts of current. They adapt to both transmitted and reflected illumination (sun light where available) and maintain a uniform contrast against rising luminance levels. They are used by Hughes Aircraft in its liquid crystal light valve system with resolutions up to 50 line pairs per millimeter (lp/mm) and image areas of 50mm diameter. For the most part, the thermal sensitivity of liquid crystals has limited their military utilization. However, HMDs employing non-see-through combiners have employed color light emitting diode (LCD) image sources with reasonable success.

Already used in dome simulators, lasers have only recently been considered for cockpit application. When used for dome projection, the lower power output of the laser is wasted by the massive inefficiency of diffuse reflection from the dome surface. For cockpit purposes, especially in an HMD, specular conservation of the laser's light should result in useful displays using milliwatt continuous-wave lasers. That the laser is quite bright is apparent from the fact that staring into a laser of this power can result in burning the retina; obviously, a primary concern is safety, for the laser should not be focused and allowed to dwell on the retina.

There has been some discussion that, because a laser emits coherent light, less power might be needed for a display. This is a misconception: it takes just as much power with a laser to produce a subjective impression of brightness as it does with any other source of light. The difference is that the laser can be strictly controlled, while an incandescent light squanders its power by radiating it off in all directions, only a few percent of which can be collected with the lenses used in display optics, also, much of the radiation is in the infrared portion of the electro-magnetic spectrum. For raster information display to the human, the cathode-ray-tube (CRT) has the advantage of persistence (if it is not too long)

that the laser does not. Therefore, either high power levels, which may be undesirable, or high scan and refresh rates are needed to suppress flicker problems. Higher scan rates may exceed the practical bandwidth limits that can be achieved with a laser scanned display system.

For simulators, extremely bright conventional xenon arc sources can be coupled with devices known as light valves, to produce very bright color images. However, suitable light value devices for HMDs used in military aircraft cockpits have yet to be developed.

THE MINIATURE 'MONOCHROME' CATHODE-RAY-TUBE (CRT)

The great strides being made with solid state image sources have application to some military display systems. Even so, significant advancements have also been made in miniature monochrome CRT technology, which still makes them the current best choice for most HMD applications. The terminology 'monochrome' is applied loosely here, as it is understood that we are not talking about a single frequency in the visual spectrum, but a dominant narrow band of frequencies that may also have several lesser spectral peaks at other wavelengths that make up the told visible light coming from the CRT. The best distinction is that visual images are formed through variations in luminance levels (gray levels) only and not by differences in color.

First, in the spirit of completeness and fair play, it is necessary to acknowledge some of the more important of the CRT's well known disadvantages. These include: (1) its long front-to-back distance that makes it difficult to package into any type of military helmet assembly, (2) its requirement for special high-voltage power supplies and often high-current deflection circuitry, (3) its weight (due in part to a lack of investment in new packaging technologies), and (4) its requirement for production methods that lead to some hand assembly (making it difficult to achieve repeatability in product and low production costs).

Yet, despite these disadvantages, it is also true that, within the time frame of most of today's current military production programs, the CRT represents perhaps the only viable solution for HMD applications. Besides their basic light conversion efficiency and superior resolution performance in small format sizes, there are other reasons for selecting the CRT. Many of the most important reasons stem from system requirements that other types of available image sources cannot support as well as can the CRT. Among them is that the CRT image source does not impose a strict allocation of display elements across the display format whose relative size and activation characteristics are fixed. Therefore, horizontal/vertical smoothing (antialiasing) techniques may be applied to smooth the appearance of straight edges (particularly from man-made objects) that cross the scanning format diagonally, producing staircasing effects and visual artifacts. Generally, a solid state display requires several times the inherent resolution of a CRT to match the apparent smoothness of the CRT's imagery. Since current miniature CRTs can provide in excess of one million resolution elements, solid state displays for HMDs have significant performance barriers to overcome. In small sizes they currently have much lower resolution than CRTs. In addition, a CRT image source may present randomly-written vector graphic information, providing only smooth line segments at any orientation on the display. This symbology may be updated at refresh rates much higher than normal video field rates to achieve much brighter peak line luminance levels for daylight viewing. This is possible by taking advantage of optimum charge pumping techniques, which some of the new rare earth phosphors permit. For these reasons, the CRT image source and the electronics necessary to support its use will be the primary focus of this section.

SOME TYPES and CONFIGURATIONS of MINIATURE CRTs AVAILABLE TODAY

As shown in Table 4-1 and Figure 4-2, arrays of different sizes now exist for miniature CRTs. This represents a significant change from the early 1980s, when essentially one size of miniature CRT existed for use with HMDs. The smallest are generally used for the display of symbology and, as one progresses to larger CRTs, one finds they are used for the display of either symbology or imagery. The maximum anode potential also increases with size, as one would expect. It is also generally true that, as the FOV of the HMD and its magnification of the image source format increases, the format size, and therefore, the outside diameter of the CRT, must be increased to permit reasonable optical system f-numbers. Display resolution and contrast performance are also usually improved with an increased CRT format size.

CRTs are normally delivered in a single cylinder shape with one contiguous mumetal shield with its leads soldered and potted at the back of the tube. They may also come in a dual cylinder package with a larger diameter mumetal shield over the deflection yoke area and a smaller diameter shield over the back of the CRT. Again, the leads are normally soldered to the tube pins and then potted in place for about two inches of length to provide some strain relief and insulation. As of 1992, however, it is possible to obtain at least the 19mm format CRT in a dual cylinder package with removable connectors that eliminate the need for potting compounds and provide better performance while also resulting in less total weight for the complete CRT package. Other package sizes will undoubtedly appear with removable connectors as someone steps in to fund the development costs for custom molds, etc.

The internal structures that comprise the CRT have, and continue to undergo, changes, resulting in more diversity to meet special requirements for particular HMD systems. The most important subcomponents are the phosphor/faceplate system, the electron gun design, the cathode, and the deflection yoke. More will be said about each of these areas later in the course, but it is worth summarizing some of features most apparent to the user as a point of reference for further discussion.

Besides size and shape, the most noticeable difference between miniature CRTs is their faceplate system. As summarized in Table 4-2, miniature CRTs generally employ either a fiber optic or glass faceplate. Generally, the design requirements of the HMD optics plays the biggest role in determining the type of faceplate used. However, phosphor type can also influence faceplate selection. Three general classes of phosphors are used, or have been developed, for use in miniature CRTs. These are particulate phosphors, sputtered phosphors, and single crystal phosphors. Particulate phosphors, which came first in developmental history, have the most widespread use and color range. Each manufacturer of phosphors, and, indeed, many CRT manufacturers, have their special processing methods for particulate phosphors to optimize resolution, luminous efficiency, contrast and life characteristics. Particulate phosphors may be used with little difficulty with either glass or fiber optic faceplates. Sputtered and single crystal phosphors offer improvements over particulate phosphor systems for certain characteristics, such as resolution performance. However, because of either available processing techniques or their requirements for higher processing temperatures, they can only be used with standard glass, or in some cases, hard glass (e.g., sapphire) faceplates. More will be said about phosphors later in the course.

Deflection yoke characteristics are also impacted significantly by visual performance design requirements and, as shown in Table 4-3, come in a variety of configurations to meet requirements and, of course, CRT size. The table shows only magnetic deflection yoke parameters, as electrostatic deflection is employed infrequently in miniature CRT applications. Generally, yoke inductances are in discrete ranges located at 15 to 20 microHenries (uH), and then jumping to about 100 to 150 uH. Capacitance and lead resistance increase, as does the inductance. High inductance yokes usually work well for

low speed calligraphic systems and raster horizontal lines rates up to about 40 kHz (1023 at 2:1 interlace and field rates of 72 per second). For high speed calligraphic and raster scan systems, where large voltages may appear across the deflection yokes and fast settling times are required, lower inductance/capacitance yokes are usually employed. To improve signal response, low inductance yokes employ larger leads with fewer windings that result in lower inductance and resistance, and which may be laid up in the yoke in a manner that reduces intralead capacitance. However, to achieve their improved response characteristics, low inductance yokes require high-current, deflection amplifiers that are not always a system option, particularly for some fixed wing fighter aircraft applications.

MINIATURE CRT PERFORMANCE

As mentioned earlier, the performance requirements placed upon the CRT normally have their primary origin in the application-specific requirements imposed by the HMD. Figure 4-3 depicts the direct impact on miniature CRTs of certain image source parameters due to the requirements for good HMD display contrast and resolution, especially when the HMD employs a see-through combiner. CRT line widths must be kept small, and active area format sizes made as large as possible. Weight constraints yield an overall maximum allowed CRT diameter of about one inch. Line rates, refresh rates and, as possible, anode potentials, must be increased to balance resolution and light conversion efficiencies. At the same time, faceplate contrast must be preserved so that individual adjacent resolution elements remain distinct and discernible to the eye. This requires a high-efficiency, fine grain-size phosphor formulated for optimum light emission/transparency and thermal conductivity, coupled with a faceplate system, such as those using fiber optics, which offer improved contrast.

Other considerations, having their origins in system integration issues, make the miniature CRT a desirable image source for HMD applications. One important issue involves the mapping of the CRT's format into the display optics image space. For binocular HMD designs, particularly designs where the monocular fields are partially overlapped, F-theta mapping, which provides constant angular resolution over the display FOV, is often the best, indeed, only choice for the mapping of a display system's angular resolution. However, F-tangent theta mapping, where the tangent of the field angle is proportional to the image source chordal height, represents no-distortion mapping condition. For HMD designs, in general, F-Theta mapping also provides benefits in optical performance and weight. F-theta mapping, where the image field angle is proportional to the image source chordal height, yields pincushion distortion. Therefore, some form of compensating distortion, nominally representing barrel distortion, must be introduced into the image source format. Solid state displays with their fixed formats, cannot achieve this variable mapping across their formats while CRTs can, albeit with some variation in resolution performance across the format. Figure 4-4 depicts the mapping relationships between the eye, HMD, and CRT and shows the derivation of the relationship for the required correction. Distortion by the HMD optics of the CRT imagery, as shown in simple graphical form by Figure 4-5, corrects or linearizes the virtual image viewed through the HMD optics.

Another advantage of the CRT is that some of the artifacts associated with scanned displays can be mollified. Any display using a scanning process for information display is susceptible to aliasing problems, particularly for man-made objects whose edges fall diagonally across the scan structure. Unlike most solid state displays, a CRT's imagery may be submitted to antialiasing processing to help linearize diagonal edges presented in the CRT's scan, as shown in Figure 4-4. This technique is particularly helpful when the scene presentation of the HMD is driven by the operator's head position and orientation as derived from helmet-tracking systems.

Substantial gains in the performance of miniature CRTs during the latter part of the 1980s were made by first ensuring that the major problem areas limiting performance were understood. These are listed in Table 4-4. Improvements in the problem areas listed in

Table 4-4 had to be made in the context of the design limitations imposed by the electromagnetic deflection(EMD)/electrostatic focus lens (ESFL) system, which has been found to be most suitable for miniature CRT applications. A representative CRT design, showing the major relationships between internal components, is diagrammed in Figure 4-6. Although new and promising alternatives are being investigated, nearly all EMD/ESFL designs for CRTs use either (1) bipotential lenses or, (2) unipotential or einzel lenses. In general, better center resolution is achievable with bipotential lens CRTs than unipotential lens CRTs, because of the more favorable beam diameter magnification value of bipotential lens designs. A first cut at determining the magnification and, therefore, beam spot size (ignoring the effects of the phosphor faceplate system) may be made as shown in equations 4.1 through 4.3.

$$\text{Geometric Magnification} = M_1 = Q/P \tag{4.1}$$

Where: Q = Distance from CRT Deflection Center to Screen
P = Distance from G_1/G_2 Crossover to Deflection Center

$$\text{Electronic Magnification} = M_2 = (V_3/V_4) \tag{4.2}$$

Where: V_3 = CRT Focus Voltage
V_4 = CRT Final Anode Voltage

$$\text{Overall Magnification} = M_3 = M_1 \cdot M_2 \tag{4.3}$$

For the CRT shown in Figure 4-6, which might operate at an acceleration potential of 13 kilovolts, and nominal focus potential of 2.5 kilovolts, a value for M_3 of 0.266 is obtained. This value may be multiplied by the virtual crossover diameter, supplied by the CRT manufacturer, to determine a first order approximation to spot size, ignoring phosphor/faceplate system contributions. Unipotential lenses give better center-to-edge uniformity than bipotential lenses. This disadvantage can be overcome by using shaped fiber optic faceplates, which minimize deflection defocusing, and using dynamic focus voltage correction, which minimizes focus lens aberrations while maintaining the significant spot minification advantage demonstrated by equation 4.2.

An accepted method of determining a figure-of-merit (FOM) for CRT performance, which is, in essence, one for spot size or resolution, for a given luminance level, is to determine the RSS (square root of the sum of the squares) of the individual contributing factors to CRT spot size. Such a relationship, presented in slightly different form in many references on CRTs, is given in equation 4.4. Recent miniature CRT design emphasis has focused on maximizing the CRT's final anode potential, while remaining within safe operating limits, investigating the effects of increasing the G_2 voltage and raising G_1 cutoff, maximizing the effective cross-sectional area of the focus lens, improving deflection yoke characteristics, and optimizing phosphor grain size, composition, and deposition techniques.

Raising the final anode potential effectively provided more luminance for the same beam current. Utilization of a lower current, and a higher voltage operating mode meant that, for particulate phosphor screens, longer phosphor life was achieved. Also, at 12 kilovolts or more, space charge spreading effects became negligible with the beam currents and beam travel distances found in miniature CRTs.

Higher anode potentials has meant a stiffer (more difficult to deflect) beam for the magnetic deflection yokes to steer. Therefore, new, higher current, low inductance/low capacitance deflection yokes were designed. These new yokes also run cooler at higher deflection coil currents. The deflection yokes are driven by appropriate highly-linear deflection electronics circuitry that can support the high video line rates, often needed

for HMD applications. The total spot diameter at the viewing surface, given by equation 4.4, is the sum of contributions from six sources:

$$d^2_{tot} = d^2_{1st\ ord} + d^2_{spher} + d^2_{astig} + d^2_{sp\ chg} + d^2_{phos\ scr} + d^2_{misc} \quad (4.4)$$

Where:

d_{tot} = Total Spot Diameter Measured at CRT Viewing Surface

$d_{1st\ ord}$ = Diameter of First Order Contribution (Magnification of Grid 1/Grid 2 Crossover)

d_{spher} = Diameter of Spherical Aberration Contribution

d_{astig} = Diameter of Astigmatism Contribution

$d_{sp\ chg}$ = Diameter of Space Charge Contribution

$d_{phos\ scr}$ = Diameter of Phosphor Screen Contribution

d^2_{misc} = Miscellaneous Aberrations Introduced by Magnetic Deflection, etc.

Maximum focus lens diameters and gun limiting apertures have been successfully implemented in an integrated CRT design. These improvements, coupled with a shaped faceplate, the implementation of dynamic focus correction into the CRT drive electronics, and lengthening the CRT slightly so that the deflection yoke assembly does not overlap the focus lens element, have effectively reduced aberrational/astigmatic contributions to about 10-15 percent of the total spot size. This may represent a practical limit to a reduction of these contributions to spot size, and leaves only first order contributions and phosphor screen effects, where further reductions might be obtained.

The major factors that contribute to first order spot size are interrelated and expressed by Langmuir's equation (equation A3.19, from Moss's book "Narrow Angle CRTs"), as given here by equation 4.5. Its form is derived for narrow-angle beam assumptions; i.e., higher order contributions to spot size are negligible, because the radial displacement and angle of the beam are kept small. Equation 4.5, then, represents an upper limit for display performance (ignoring phosphor screen contributions), and, once a CRT has been optimized for a given set of operating characteristics, indicates the only possible ways that higher current densities (more luminance for a given spot size) can be achieved. A closer look at equation 4.5 shows that there are essentially four parameters which may be varied to increase peak current density at the phosphor screen: (1) increase the final acceleration potential (increasing this parameter provides more display performance improvement than any other design change), (2) increase the angle of convergence at the screen, (3) reduce the operating temperature of the cathode, and (4) increase the peak emission current capability of the cathode. The acceleration potential has already been raised, and 13 kilovolts appear to be a maximum reliable operating potential. Modifications to the triode and focus lens design, within the allowed dimensional limits of miniature CRTs, have also brought the angle of convergence to near its absolute maximum. Therefore, the designer is left with the option of reducing the object beam diameter.

$$P_S = P_C((eV/kT)+1)\sin^2 \mathbf{q} \qquad (4.5)$$

Where: P_S = Peak Current Density at Screen

P_C = Peak Current Density at Cathode

V = Final Acceleration Potential

T = Cathode Temperature

e = Electron Charge

k = Boltzman's Constant

$\mathbf{q}$ = Maximum Half-Angle of Convergence at CRT Screen

A practical way to accomplish this reduction of beam diameter is to reduce the G_1 aperture (see Figure 4-6). The relationship between the electron beam crossover diameter and control grid aperture (to a first order approximation) is given by equation 4.6, which shows that d_{CO} is proportional to CRT control grid diameter. This proportionality holds for equal cathode currents, but not for equal CRT drive voltages. Equation 4.6 seems to indicate a simple straightforward solution to obtaining a higher resolution CRT display. However, other CRT electron gun relationships quickly begin to dominate the overall design problem as G_1 apertures are decreased.

$$d_{CO} = k\,(D_{g_1}) \qquad (4.6)$$

Where: d_{CO} = Electron Beam Crossover Diameter

D_{g_1} = CRT Control Grid 1 Diameter

k = Gun Design Dependent Constant

Of major importance is the effect on electron beam cutoff voltage and, ultimately, peak cathode loading, as described by the relationship given by equation (4.7). This relationship shows that cathode loading is inversely proportional to the square of the G_1 diameter and rapidly increases as that diameter is reduced. Further, the electron beam cutoff voltage, which is approximately proportional to the 2/3 power of G_1 diameter, rapidly decreases as G_1 aperture is reduced, requiring electron gun part spacings to be reduced proportionately.

$$P_C = k/(D_{g_1})^2 \qquad (4.7)$$

Where: P_C = Peak Cathode Loading

At the G_1 aperture sizes indicated for miniature CRT resolution requirements, the gun element spacings rapidly approach tolerances that are difficult to maintain, as shown by some of the Air Force's recent miniature CRT development efforts. Manipulation of the

above relationships also has a significant impact on peak cathode loading and, ultimately, the useful life of the cathode and CRT itself. Results obtained for several G_1 aperture sizes of particular interest for miniature CRT applications are shown in Table 4-5. For the conditions given, a 50 percent duty cycle represents average worst case conditions for each field or refresh of video imagery/symbology for most helmet display system applications, because of beam blanking time and different luminance levels across the display imagery. However, 100 percent duty cycle conditions can be reached for short periods for daylight applications of stroke symbology, and must be considered during the CRT design and cathode selection process. Since the life of standard oxide cathodes is reduced considerably when peak loadings of greater than 2 amperes per centimeter squared are used at high duty cycles, either G_1 apertures must be limited to about 13 Mils or suitable substitutes must be found for the standard oxide cathode.

Electron gun efficiency (normally described as the ratio of cathode current actually reaching the phosphor surface to overall cathode current actually emitted at the cathode) and G_2 voltage effects must also be considered when G_1 apertures and electron beam cutoff voltages are manipulated. Equation 4.8 shows the inverse relationship between electron beam crossover diameter and G_2 voltage when the cathode current is normalized. Thus, raising the G_2 voltage can aid in reducing electron beam spot size. However, as G_2 voltage is raised, the effective electron beam cutoff voltage is raised, requiring more video drive to achieve a given line brightness. Excessive video drive requirements can limit the video bandwidth of the display electronics video amplifier which, for 1000-by-1000 element noninterlaced applications running at 60 frames per second, is already above 60 megahertz. In addition, voltage breakdown considerations (field emission) for the small gun part spacings quite rapidly become critical as G_2 voltages are raised above approximately 1000 volts. Finally, gun efficiency can be rapidly reduced. Similar gun designs whose internal triode designs have been optimized with G_2 voltages of 400 and 800 volts have shown reductions in gun efficiency from roughly 50 percent to 20 percent respectively. This result exacerbates an already severe cathode loading problem, and also heat dissipation.

$$d_{co} = k(1/E_{G_2}) \tag{4.8}$$

Where: E_{G_2} = CRT Control Grid 2 Voltage

Tables 4-6 and 4-7 depicting test results with some recently-developed Hughes Display Product's CRTs demonstrate how bright improved versions of today's CRTs can be. They achieve these results at the expense of fairly high cathode loading and somewhat higher linewidths than some very demanding applications can tolerate. Limiting the G_1 aperture might improve linewidth, but at the expense of even more severe cathode loading.

ALTERNATIVE ELECTRON-GUN DESIGNS for MINIATURE CRTs

These problems, the need for a truly bright CRT for daylight/see-through/symbology HMD applications, and the need in some applications for a CRT that can provide stable resolution performance for night sensor presentations with modest resolution requirements while transitioning to high luminance daylight symbology presentations, has led to searches for design alternatives to the typical bipotential-lens gun design shown in Figure 4-6.

One new alternative CRT that has given rise to optimism had its origins in a joint development effort between the Armstrong Laboratory and Hughes Aircraft Display Products. Named for its distinguishing Decelerator Pre-focus Lens (DPFL) gun, the DPFL

CRT has shown much promise. The most fundamental difference between this gun design and the standard bipotential-lens CRT is that it has an additional control grid between the G_2 and G_3 grids, as shown in Figure 4-7. In a conventional miniature bipotential gun CRT, as the ratio of G_3 to G_2 voltage decreases, so does the current efficiency of the gun. The addition of the extra grid (denoted here as G_d), operated as a decelerator at the same or a lower potential than the G_2 grid, effectively increases the ratio with respect to the G_3 potential. The increased ratio (G_3/G_d) results in a less divergent beam, and thus more of the beam can pass through the gun limiting aperture to the phosphor screen, raising the effective gun efficiency. One slight drawback noticed with preliminary CRTs employing these designs is that the minimum spot size is somewhat larger than the conventional design for lower beam currents, but its spot size increases much more slowly as beam current is increased.

These characteristics and preliminary data taken from the few DPFL tubes that exist suggest that this type of CRT-electron gun combination offers a number of very desirable characteristics. Among them are: (1) nearly constant linewidth over a wide range of modulation voltages, (2) low modulation defocusing, (3) minimization of focus lens spherical aberration, and (4) selectable gun efficiency.

Preliminary results with some recently-built DPFL CRTs at final anode potentials of 13,000 volts are shown in Table 4-8. The Air Force has designed ruggedized display electronics for engineering research with additional variable control grid voltages so that CRT designs of this type can be accommodated for test and evaluation under both simulator and field conditions.

ALTERNATIVE CRT CATHODES

DISPENSER CATHODES

It has been evident for many years, and especially because of recent results obtained with improved electron gun designs, that cathodes capable of operating at higher current loading densities and with better operating life characteristics could have a major impact on miniature CRT performance. Standard oxide cathodes can be operated at somewhere between 1 and 2 amps/cm^2 if normal lifetimes (> 1000 hours) are to be obtained. The search for a satisfactory replacement to the standard oxide cathode and its variants used in miniature CRTs has been ongoing, as scarce funding permitted, for more than a decade. It now appears that improved oxide cathodes incorporating scandium, etc., may be about to bring a change to the operating levels and lifetimes of oxide cathodes. Offering hope of even greater improvements in cathode performance are advanced versions of matrix type cathodes and low noise/low power dispenser cathodes.

A well known solution to higher current cathodes is the 'dispenser' design in which a porous tungsten matrix, impregnated with barium compounds, is heated to a sufficiently high temperature to release or 'dispense' barium at a higher rate than practical in an oxide cathode, thus providing a higher emission current. A long lifetime is achieved through a large reservoir of available barium within the matrix. A diagram of the basic dispenser cathode structure is shown in Figure 4-8. In attempting to employ dispenser cathodes in CRTs, where, as already shown, higher current densities would increase performance, a number of significant difficulties have arisen. Among them are erratic performance due to miniaturization problems and electrode leakages and thermal grid electron emission arising from higher operating temperatures.

A number of good candidates for the miniature CRT now exist with dispenser cathodes. Among them are scandate, mixed matrix, cavity reservoir, and M Type dispenser cathodes. One such recent result with Thomson Tubes Electroniques dispenser cathodes, shown in Figure 4-9, demonstrates the improvements to cathode current emission density

and life compared to standard oxide cathodes. Other vendors including NJR Corp., Mitsubishi, and Matshushita in Japan and Semicon in the United States, appear to be offering superior cathodes. The problem that arises, though, is that proper cathode activation is an intricate procedure requiring the proper facilities and a full understanding of the entire cathode activation process. The current situation regarding the use and activation of these new cathodes is that miniature CRT manufacturers who make superior electron guns would rather receive the cathodes and learn how to activate them, while the cathode manufacturers, though they release activation information to CRT manufacturers, claim that the activation process is best performed by them. This author is not aware of a satisfactory solution to this problem as of the date of this course.

LOW-VOLTAGE (LV) FIELD EMITTER ARRAY (FEA) CATHODES

Use of field-emitter array cathodes for miniature CRTs have been investigated for more than 15 years. As shown in Figure 4-10, the FEA cathode structure consists of a series of emitting microtips (emitters) micro spaced at about 4-6 microns from adjacent cathodes. Each emitter can generate from 10 to 20 microamps of current. These emitters can be organized in arrays with dimensions similar to conventional miniature CRT cathodes to provide very high beam currents and current loading densities (> 8 amps/cm^2). This type of cathode does not exhibit the same aging problems associated with other cathode types or the grid emission problems often associated with dispenser cathodes. Because the electron sources (emitters) are spatially distributed and the field emission process is very nonlinear, the emitters can be gated to turn on individually or in groups. These characteristics imply that a flat, very thin CRT structure could also be built using this type of cathode. The existence of a flat CRT providing either monochrome or full color could be a real boon to some HMD applications. The fact that FEA cathodes will also operate in a poorer vacuum than needed for other cathode types also enhances their usefulness. Recent problems with emitter self-destruction and breakdowns in the resistive materials due to high field gradients seem to have been overcome and interest has been renewed in applying this technology for use in HMD miniature CRTs.

ALTERNATIVE PHOSPHOR/FACEPLATE SYSTEMS for MINIATURE CRTs

SINGLE CRYSTAL and SPUTTERED PHOSPHORS

The remaining area left for obtaining performance improvements is phosphor screen characteristics. A significant impediment to past performance improvements in this area had been knowing what the actual beam diameter was, just prior to beam impact on the phosphor. This diameter could then be compared to the spot size of light emanating from the phosphor after impact of the beam. Armstrong Laboratory had a significant parallel effort in effect for several years with AT&T, Bell Laboratories to develop improved versions of single-crystal phosphors (SCP) that, compared to conventional oxide cathodes, had superior thermal characteristics and did not suffer coulombic degradation which causes diminished light output for the same power input. Their cathodoluminescent qualities also produced a spot of light that was almost the same diameter as the electron beam spot impinging on the rear surface of the phosphor. While these materials exhibit superior contrast at all drive levels, they have not produced the external luminous efficiencies originally hoped for. However, they have proven to be very significant design tools, and have provided important technical insight into the improvement of particulate-phosphor CRT screens. Fabricated in split-screen versions, where one-half of the CRT screen has an activated SCP, and the other half a given formulation of a particulate phosphor, the CRT designer could then know the contribution to spot size made by the particulate phosphor by measuring the change in spot size as the electron beam scanned across the two media. This has allowed the importance of a number of particulate phosphor parameters to be investigated, including; (1) the optimization of phosphor thickness and, therefore, its transparency to light generated by the e-beam for a given acceleration potential, (2) the optimization of grain size mixtures, to achieve high resolution, high

luminous efficiency, good thermal conductivity and good operating life characteristics, and (3) the evaluation of phosphor deposition processes that yield good percent coverage of the screen, and optimized phosphor grain packing. These processes, although much refined, are still undergoing further improvement.

Figure 4-11 depicts the performance gains achieved for an improved miniature CRT, utilizing an optimized particulate phosphor screen and improved electron gun design developed as part of a joint Armstrong Laboratory and Hughes Aircraft Company development program. For the reference CRT, specified in Figure 4-11, measured at 50 percent peak luminance, line widths of 0.75 mils (19 microns) and 1.0 mils (25.4 microns), luminances of 1100 and 1300 ft.-Lamberts were obtained. For the improved CRT measured at the same line width conditions, peak line luminances of approximately 4300 and 7350 ft.-Lamberts, respectively, were achieved.

As mentioned, the SCP effort was not as successful as had been hoped. While the internal light conversion efficiencies were comparable or, for some formulations, better than the best particulate phosphor screens, the light trapping associated with the SCPs reduced the external light flux in the forward direction by a factor of $1/2n^2$, where n is the index of refraction of the SCP film. The n^2 factor reflects the increase in solid angle in going from the SCP with index n to air. The factor of 2 reflects the loss in luminance in the forward direction with an isotropic emitter (one with the same amount of power per solid angle per unit area in every direction) as compared to a Lambertian emitter of the same internal light conversion efficiency. Attempts to ameliorate this problem for HMD application, using immersion optics and/or selective etching of the SCP film to produce light diffusion comparable to a Lambertian emitter, did not result in systems suitable in weight or size for HMD use or that were reproducible in a reliable fashion. However, for some HMD applications not requiring maximum luminance performance, the superior resolution and contrast properties of SCP films can be exploited to achieve remarkable results.

As a result of initial experiences with SCP development at Bell Laboratories, parallel investigations were begun to achieve a phosphor screen design that could produce external light conversion efficiencies comparable to high performance particulate-phosphor screens, yet maintain some of the superior properties of SCP films, such as enhanced coulombic degradation performance, good heat transfer, screen uniformity, and resolution. One approach taken that is now producing encouraging results was the radio frequency (RF)-sputtering of highly-scattering thin films that were comparable to true Lambertian emitters which could also be deposited on a low refractive index substrate to reduce the n^2 factor reduction in external light conduction. Two of the phosphor formulations studied were Tb^{3+}:$Y_3Al_5O_{12}$ (Tb:YAG) and Tb^{3+}:$Y_3Al_3Ga_2O_{12}$ (YAGG), known commercially as P53 [02]. After substantial investigations into the best configuration for the RF furnace and substrate materials, and intensive studies of important variables influencing the quality of the film deposition/activation processes, it has been possible to install these materials into working miniature CRTs. Preliminary tests with Tb^{3+}:YAG in a working 27 millimeter diameter CRT operating at 13,000 volts final anode potential show excellent results, as documented by the performance depicted in Figure 4-12. For the sputtered phosphor, line width remains superior, while luminance remains essentially the same to 5000 ft.-Lamberts where saturation effects for the smaller particle size sputtered phosphor begin to cause a rolloff in brightness as the e-beam power input is increased. This level of luminance and resolution performance is suitable and highly desirable for many HMD applications. Faceplate contrast performance tests must also be rigorously assessed before the suitability of sputtered phosphors for miniature CRTs will be fully known. It should also be noted that, due to the high temperatures required to anneal sputtered phosphors, use of shaped-fiber optic faceplates is currently not feasible to minimize deflection defocusing effects. However, laser annealing techniques offer hope of overcoming this limitation.

INTAGLIATED FOB FACEPLATES

Complete exploitation of phosphor improvements that have recently been made requires consideration of the performance contribution to display discernability made by the phosphor's close association with other portions of the faceplate system. Some recent work has concentrated on improvements that might be made by light enhancement films and intagliation of the fiber optic faceplate. Films may cause scattering and some loss of electons.

Fiber optic faceplate intagliation is shown in Figure 4-13, where the core material is etched or dissolved away, leaving the cladding to form a receptacle for the phosphor grains, seems like a logical method for limiting light scattering and improving faceplate contrast. Recent efforts have made progress in obtaining uniformity of the etched holes and determining the best methods for packing the phosphor grains into the holes, but other portions of the fabrication process appear to need further work. At this time, with only a few CRTs built and tested using this technique, it appears that faceplate contrast is being improved, but the improvement is less than expected.

Use of glass faceplates with antihalation coatings have produced results that are even more of a mixed bag. Only a few tubes have been built to test the efficacy of these coatings, but the results have shown larger linewidths and some birefringence, indicating how important it may be to ensure that the coating and phosphor characteristics are closely matched.

COLOR IMAGE SOURCES for HMDs

In recent years, suitable miniature color image sources for HMDs have been sought after more aggressively. Their use in no- see-through HMDs seems to have more potential than for see-through HMDs, but, at night, even see-through HMDs may benefit significantly.

A number of attempts at building miniature color CRTs have been made. Among them are field-sequential systems, beam penetration systems, and post-deflection acceleration systems. None have been found to be really useful. Though someone may yet design and build a truly outstanding miniature color CRT, it is probably true that the demands placed on this device, where the information and light generation functions are combined, will not permit it to be competitive with alternative approaches.

Among the more promising alternatives to be presented include laser color generation schemes, new types of cathode systems that lead to new types of electron gun triodes or eliminate them, and liquid crystal devices.

LASER COLOR IMAGE SOURCES

Laser-generated color image source schemes seem to offer the promise of high-intensity, high-resolution color. The basic idea behind most schemes is to pipe laser light through a helmet-mounted fiber-optic ribbon (containing one fiber per active line on the display) and onto a spinning mirror to create a raster. The scan lines are not normally written in parallel. The apparent purpose of using a multi-fiber ribbon is to avoid the need for a

mechanical vertical-scanning system. Full color can be produced by sandwiching three ribbons together and modulating them slightly out of phase with one another so that the red-green-blue (RGB) pixels overlap properly. Many different schemes appear to be available for modulating the light, including variations of linear lanthanum-doped lead zirconte titanate (PLZT) arrays or piezoelectric pistons, or linear arrays of Kerr-effect modulators.

BALLISTIC ELECTRON LUMINESCENT TRIODE (BELT) and FEA CATHODE IMAGE SOURCES

A BELT is a matrix 'super'-cathode device, addressing a conventional phosphor triad screen (although the phosphors themselves would probably be unconventional). The BELT operation employs electron tunneling to produce electrons of non-space-charge limited, extraordinarily large current densities of narrow energy spread required for high display luminance (brightness). FEA cathodes, already described in the discussion on monochrome miniature CRTs, can obviously be organized as a matrix of row-column addressed emitters that are aligned with the RGB phosphor matrix. The advantage is a simpler CRT gun structure that operates at lower vacuums than the conventional CRT and eliminates the CRT front-to-back length, allowing an essentially flat CRT of perhaps 3/4 inch thickness to be constructed. However, the lower anode potentials associated with a flat CRT will likely not be able to attain the high luminance levels desired for many HMD applications.

Color image sources based upon lasers or advanced types of cathodes seem to offer promise, but appear to be farther in the future than miniature color image sources that might be constructed now using LCD technology.

LCD SUBTRACTIVE COLOR IMAGE SOURCE

Figure 4-14 shows an example of a subtractive color LCD now under development. The (off-helmet) illuminator for the LCD pumps light into a thin, noncoherent fiber-optic cable. The illuminator consists of a xenon lamp, reflector, cold mirror (to remove IR), UV filter, RGB filter, and a lens which focuses the light onto the cable-end. The RGB filter spectrally tunes the light to match the light-valve's spectral selection characteristics.

At the other end of the cable, the light enters a premodulation section consisting of a collimating lens and field-stop. The field-stop limits the collimated light beam diameter to the light-valve's physical dimensions.

Next, the light enters the light-valve, which contains two major sections: (1) a luminance-modulation section, consisting of a chromatically-neutral LCD with polarizer; and (2) a chromatic-modulation section consisting of three guest-host LCDs with polarizers. The three guest-host LCDs contain yellow (-blue), magenta (-green), and cyan (-red) dichroic dyes, respectively. These LCDs use liquid crystal to control the orientation of the dye molecules and thereby vary from transparent to fully colored (i.e., the liquid crystal (LC) does not modulate light directly - it only rotates the dye molecules). In principle, the three guest-host LCDs can also perform the luminance-modulation function; however, the use of a separate LCD for this purpose will give the demonstrator better luminance contrast and color purity. Future development can presumably eliminate the fourth LCD.

Finally, the light passes through a diffuser, which softens the edges of the pixels' sharp luminance profile, and enters the HMD optics. Figure 4-15 shows how a prototype system might appear as part of a HMD system.

This design approach seems to show reasonable promise. Only its completion and test will be able to confirm this promise. There are some special design issues with the subtractive color approach that are worth mentioning.

SPECIAL CONSIDERATIONS for SUBTRACTIVE COLOR IMAGE SOURCES

Rotation of the dye molecules inside one of the three subtractive cells alters the display's spectral transmittance function in a manner that is equivalent to adding dye to a beaker of water, as shown in Figure 4-16. If the display is illuminated with broadband white light, the transmitted light changes gradually from white to increasingly colored, as depicted in the leftmost portion of Figure 4-16.

The center diagram of Figure 4-16 shows this same transition on the Commission Internationale de L'Eclairage (CIE) 1931 chromaticity diagram. Initially, the chromaticity plots at the center of the diagram, in the same location as the broadband white illuminant. As the dye molecules rotate, the cell's chromaticity shifts out toward the diagram's perimeter, becoming increasingly saturated. Since each cell controls one of the display's color channels, this means that chromaticity and luminance for each channel will covary, given a broadband illuminant. This, in turn, means that exercising proper control over the display's color becomes quite complicated.

A color CRT, on the other hand, is much better behaved. The chromaticity of a CRT's RGB channels is determined by the phosphors. Exciting a phosphor to varying degrees changes the amount of light that it produces, but has no effect on the light's spectrum. Therefore, (to a first approximation anyway) the chromaticity of a CRT's RGB channels does not vary with luminance. This invariance is depicted in the rightmost portion of Figure 4-16. The solution to this problem is to avoid the use of a broadband illuminant.

The ideal illuminant contains only three wavelengths, chosen to provide satisfactory red, green, and blue colors (as well as a satisfactory white when all three are mixed together in proper proportions.) In this case, the channel chromaticities will be invariant, because the display cannot shift energy from one wavelength to another. Instead, the display can vary only the proportion of each wavelength that is transmitted.

Ordinarily, the luminances of a color CRT's RGB channels can be varied without affecting one another, i.e., there is no interaction, or 'crosstalk.' Figure 4-17 illustrates this issue. If the dyes in the subtractive display had no spectral overlap (as depicted by the solid lines in the three diagrams of Figure 4-17), its color channels would also be free of crosstalk. Unfortunately, real dyes tend to have broad spectra that modulate energy outside their assigned wavelength bands, and the spectra change as the dye molecules rotate -- these characteristics are depicted by the dotted lines in the figures. The result is crosstalk that varies with cell transmittance.

Once again, the solution is to avoid broadband illuminants. If the illuminant's energy is restricted to only three suitably chosen wavelengths (or narrow wavelength bands), the opportunity for each wavelength to be modulated by the wrong dye can be minimized or even eliminated, depending on the overlap among the dyes' spectral transmittance functions.

The FUTURE for MINIATURE CRT IMAGE SOURCES

During the next four to five years, it seems likely that nearly optimum electron gun designs will appear for specific applications. It also seems likely that gun designs will become available providing good performance for day/night systems that require night raster presentations at the lower line rates and high-brightness daylight symbology. With the commercial incentive and investment that appears to be occurring in high performance cathodes, it also seems reasonable to expect that cathodes exhibiting high current loading densities (4 - 8 amps/cm^2) and improved operating lifetimes (>1000 hours) will become available for use in miniature CRTs. What is not so clear is whether phosphors with improved resolution and coulombic degradation numbers (such as sputtered phosphors) will be available to match the performance gains of the CRT gun and cathode. This is

because these types of phosphors will probably be expensive for large area displays and, thus, appear to have no similar commercial incentives for their development. Improvements in CRT deflection yokes will probably be incremental, at best. However, significant changes may begin to appear in CRT packaging, involving molded parts and metalized coatings for shielding that may affect yoke design and could result in improved form factors and reduced weight. Finally, color image sources should continue to become more viable alternatives for some HMD applications.

The CABLE INTERCONNECT for the HELMET-MOUNTED HARDWARE

It is a given that the cable interconnect between the helmet-mounted components and system electronics is very dependent on the image source type. The assumption made for the helmet-mounted cable interconnect is that the CRT will continue to be the primary image source for most near-term military-based HMD applications. Therefore, the discussion emphasizes only cable system design issues related to the use of the miniature CRT, with its attendant high-voltage operating conditions.

Ideally, the wiring harness between the aviator's helmet-mounted systems and the aircraft mission equipment package (MEP) avionics is considered to be a critical system component. Unfortunately, this has not been the case. Although a number of attempts have been made, it has really only been in the last two years that realistic solutions for disconnecting the pilot's helmet system from powered high-voltage systems during ejection or during ground-egress in explosive vapor environments have been defined. These are only now being implemented in working hardware.

A fundamental problem with using a miniature CRT is the requirement for high-voltage power and the associated problems of rapid disconnect from such power, and the associated problem of corona that can occur from the high field gradients, which can destroy the inherent properties of both the insulating material and the electrical conductor, itself. Alternatives, such as placing miniaturized high-voltage power supplies and the final deflection or video amplification stages on the helmet have been tried over the last twenty years with variable results. However, these options normally only exacerbate the already severe head-borne weight and center-of-gravity issues which adversely influenced pilot comfort.

For most systems, it is realistic to assume that the power supplies and final deflection and video signal amplification stages must reside off the helmet. This imposes a need to devise a satisfactory method of providing a safe quick-disconnect under emergency conditions. Features that might be associated with such a system are listed below.

1. Provide a viable HMD cable wiring harness(es) and connector assembly(s), to support the performance requirements of visually-coupled system (VCS) hardware that may consist of either a monocular, biocular, or binocular HMD using a miniature CRT, a helmet-mounted sight (HMS) system, or a night vision goggle (NVG) head-up display (HUD) system using a helmet-mounted subminiature CRT.

2. Provide safe in-flight pilot ejection or rapid ground egress in explosive or oxygen-rich cockpit environments while the HMD/HMS/NVG systems are operating and remain as part of the pilot's personal equipment.

3. Provide selective improvement to the signal bandwidth and noise immunity characteristics of particular signal leads in the wiring harness, as dictated by application-specific system requirements. In particular, provide a significant improvement in CRT video performance.

4. Provide field-replaceable capability of the CRTs without the need to replace, rework, or discard a portion of the quick disconnect cable (QDC) wiring harness.

5. Provide a QDC wiring harness concept that makes the placement of the helmet-mounted systems' component electronics independent of the aviator's wiring harness and missing equipment package interface.

6. Provide a design supporting simple, modular replacement of those critical components in the field that will be subjected to the most wear and abuse, thus extending the life and field reliability of the QDC wiring harness system.

These generalized requirements can be used to generate a more specific set of performance requirements, assuming that the CRT is the likely candidate image source. Tables 4-9 and 4-10 list a set of possible requirements that seem reasonable for such a system.

DESCRIPTION of the QDC WIRING HARNESS

Using Figure 4-18 as a reference, a general functional description of the QDC wiring harness and connectors can be developed. The reader should keep in mind that the performance and design features are deemed to be preliminary until a working, tested, and certified connector and wiring harness assembly is available.

The QDC system begins with a branched-flexible wiring harness assembly between the QDC and the helmet. This assembly is marked as Module III in Figure 4-18. The QDC upper half is fixed to the pilot's torso harness. The removable high-voltage connector plugs, which mate to the CRT display tubes, will have a design similar to the 'Avvion' connectors now produced by Reynolds, as shown in Figure 4-19. The CRT connectors (positions 8 and 10 in Figure 4-18) are divided into two companion connectors; one for the deflection and high voltage located near the end of the deflection yoke, and one for all other connections located at the base of the CRT. An additional connector plug will be designed and built to interface to the helmet-mounted sensor (position 9 in Figure 4-18).

The lower half of the QDC is connected to a wiring harness whose opposite end connects to a panel-mounted connector (PMC). This assembly is marked as Module II in Figure 4-18. The PMC side of the QDC would be the female side of the connector to prevent inadvertent exposure/grounding for sensitive signals and high voltages. The QDC side of the PMC will be the removable half. The lower half of the QDC on the aircraft side of the separation device would be removed or pulled free of the aviator for both normal and emergency egress. A provision could be made to mount hybrid video drive circuitry to the QDC shell and to dissipate their thermal energy on this side of the QDC.

A branched-cable wiring assembly, from the aircraft electronics interfaces to the lower half of the PMC, can be constructed on an application-specific basis. This assembly is marked as Module I in Figure 4-18. The lower half of the PMC, which is fixed to the airframe, will accept the cables from the end connectors at the aircraft electronics interfaces. This module could incorporate an optional pressure bulkhead feed-through for applications where the electronics are mounted outside of the pressurized cockpit.

An additional intermediate helmet connector has been considered. Current thinking on this issue is that the potential decrease in system reliability caused by the additional connector (always a source of reliability problems) warrants its exclusion. However, the potential loss of the helmet during ejection, and the problem of man-helmet separation following such an event, may still force consideration of this additional connector interface. The problem may also be worked by a new connector for the oxygen mask, which can be a key positive factor in helmet retention during ejection.

In Figure 4-18, it is assumed that the CRT electronics, or some intermediate location (such as at the panel mounted connector), contains crowbar circuitry that is activated by a mechanical/electronic switch associated with the make/break wiring in the QDC. This crowbar arrangement would suppress a significant amount of the stored system energy before the actual connector separation occurs. The QDC-triggered control signal could also disable the display electronics power upon connector separation, and, upon reconnecting, will restore power after a short delay. This scheme would protect the system from 'hot makes' that lead to a faster deterioration of connector contacts and removes the need for the aviator to bring his display electronics back up manually, if inadvertent connector disconnects/reconnects occur during aircraft operation. The QDC would also be 'shape keyed' to ensure unambiguous 'hookup'. Figure 4-20 and Table 4-11 respectively, show the current configuration of the QDC pinouts and identifies the function of each pin.

OTHER MAJOR ISSUES

Safely providing high voltage to the helmet-mounted CRTs and implementing a safe quick-disconnect in explosive vapor environments are very important. But there are other major issues. Among them are partial discharge effects and maintaining signal fidelity between the machine-based and helmet-mounted electronic devices.

PARTIAL DISCHARGE

Partial discharge (PD) phenomena have largely been ignored during previous attempts to build a suitable high-voltage QDC and wiring harness for HMD systems. PD generally occurs when some form of electrical activity, usually a quick increase in current or voltage, within the system results in a rapid change of the electric field configuration that causes a current flow in a conductor connected to the external world. PD can occur in solids, liquids, and gases in ways that will not affect the breakdown voltage during a high voltage 'proof' test. Yet, PD will eventually cause failure in high voltage systems, especially if the wrong design, fabrication, and material selection processes are employed. To be recognized as PD, the induced current must be sufficiently large and with sufficient repetition rate to be recognized as something other than random noise. The most common sources of PD are floating components, corona, and voids, of which the latter two are most important for the HMD wiring harness interconnect. This phenomena, its relationship to materials and material processing, and associated testing techniques for its detection and identification are being given great emphasis as part of this new development effort.

VIDEO BANDWIDTH

Improving the signal transmission characteristics of the wiring harness between the aircraft-mounted electronics and helmet-mounted devices, including even the HMS sensors, has to be a vital goal if VCS performance is to be significantly improved. The video signal transmission problem has received special consideration because of the high signal bandwidths and its implication as a limiting factor in the sensor-display system. High bandwidths require high video frequencies which are sensitive to inductance and capacitance, i.e., transmission line effects. Normally, panel-mounted CRTs used for high performance video applications have the final video signal amplification stage of the electronics mounted within a few inches of the CRT. This type of circuit component topology reduces the effects of capacitive loading and signal noise interference problems and permits very high video bandwidth performance. For the helmet-mounted CRT, as much as eight feet of cable may separate the electronics and CRT, allowing significant degradation of the video signal. Mounting the video amplifier in the helmet near the CRT normally exacerbates an already severe helmet weight problem. A solution being investigated as part of the QDC development program is to develop custom circuitry that can be mounted in the backshell of the QDC approximately 18 inches from the CRT to minimize transmission line length problems. This issue receives further discussion in Section 7 of this course.

The FUTURE

Within the next year it is hoped that versions of a 'standardized' helmet-vehicle interface (HVI) including the QDC and wiring harness will be tested in military aircraft with operational helmet displays. Interconnect standardization should improve component availability, especially for the miniature CRT image sources. And, by virtue of interface optimization, the performance of the helmet-mounted components should be measurably improved.

The HELMET-MOUNTED DISPLAY ELECTRONICS (HMDE)

Although sometimes given secondary consideration, the design and performance of the display electronics, along with the cable interface, can dramatically affect the performance of the miniature CRT. Their performance is a fundamental factor in the modulation transfer function (MTF) that the CRT can achieve. The drive electronics also control most of the important factors relating to the customization/integration of the CRT formats with respect to the HMD optical design. Two types of display electronics exist today. Those whose electronics are designed as a more or less fixed element with only the basic adjustment functions of CRT gain, offset, and focus; and those designed as general purpose systems with most or all possible adjustments made accessible or programmable by the user.

Most HMD applications dictate that the HMD be considered an application-specific device. Indeed, many applications of VCS technology have resulted in less-than-desirable outcomes, because off-the-shelf HMD systems were utilized instead of a design intended specifically for that application. It is perhaps prudent to consider a middle ground for the functionality and performance of the display electronics, one that can at least compensate for problems, such as production line variations in the CRT itself. The problem becomes complicated because of the ongoing performance improvements in miniature CRTs, which system users may desire to utilize as they become available. Some basic requirements that might be considered for most, if not all, display electronics designs are enumerated below.

1. Allow the display electronics to optimize each CRT's grid control voltages for best performance, either through serial ROM modules provided with the CRT or through storage of the necessary parameters in local memory, thus permitting CRT replacement at near-optimum performance levels for a particular CRT;

2. Permit complete system setup and adjustment, including HMD alignment pattern generation, to be accomplished from the cockpit without the need to pull boxes, adjust potentiometers, etc.,

3. Provide sufficient deflection, video, and high voltage power to support the latest advancements in miniature CRT technology,

4. As a result of the HMD's magnification of the CRT format, provide the best possible video and deflection signal quality because of the visual enhancement of deflection and video noise,

5. Provide separate video channels for raster and stroke video input to support requirements to combine HUD and sensor/computer-generated information on the display or to maximize CRT duty-cycle for symbology presented in high ambient light conditions,

6. Provide automated system input flexibility to permit the use of raster sources having a range of line rates, and to allow the internal raster generator to be synchronized to external video raster sources, and

7. Accept the HMS signals directly, to provide the right combination of raster imagery rotation and translation for a specific HMD design at the refresh rate of the HMD electronics.

The 'BASIC SYSTEM'

Figure 4-21 depicts what, for discussion purposes, might be classified as a basic HMDE along with its basic interconnects to other components of a complete VCS. The heart of the HMDE is the system electronics unit (SEU). This box contains all of the power supplies, any computerized parameter control and signal processing circuitry necessary to support a range of separate signal inputs from stroke and raster video signal source inputs for one or two miniature CRTs. It also tailors these signals for proper output to most types of miniature CRTs now available or being developed. These functions can be located some distance from the HMD itself.

The high voltage power supplies and final video and deflection amplification stages are normally located near the HMD, sometimes actually mounted on the helmet. Their exact design and arrangement is dictated by the types of video and the deflection and video bandwidths needed to accommodate the bandwidth of the incoming video signals.

Video amplifier designs may vary from differential drive designs meant to drive long cables lengths between the amplifier and CRT of eight to ten feet, to single-ended cascode designs that may be torso or helmet-mounted designed to drive short cable lengths of a few inches to perhaps two feet. Deflection amplifier designs may range from tuned deflection systems designed to drive the CRTs at one video raster rate to high-performance linear Class-A amplifier arrangements that attempt to maximize linearity and repeatability of pixel placement on the CRT for multiplexed display of raster and calligraphic video.

A separate control panel is normally included as part of the display electronics. Any HMD control panel usually must provide adjustment for luminance, contrast, and electronic focus. These basic controls become more complicated if separate luminance controls must be provided for both the calligraphic video and one or more raster video sources. Video gain and offset controls are also very useful because CRTs, being the analog devices they are, often exhibit drift. For binocular systems, separate right and left eye luminance controls may be necessary to manage image brightness differences between the eyes. Adjustments for CRT image size differences may also be required. Also, binocular systems often require some way to present alignment patterns to the eye to perform the fine electronic alignment of the images after the basic mechanical alignment of the optics has been performed. Finally, other grid voltage adjustments may be made available for adjusting such parameters as the CRT's cutoff, etc.

The HMDE SEU

Figure 4-22 depicts a simplified block diagram showing the basic display electronics signals normally encountered. The key to display electronics' designs meant to drive miniature CRTs is a full knowledge of the components and alternatives available today for implementing a more or less optimum design. The ideal system would be an all-digital design where all conditions could be reproduced or modified on-command in a repeatable manner. Yet, despite digital technology's many desirable attributes, it has yet to supplant analog technology in many areas of video electronics design. Therefore, the better designs usually combine some form of hybrid digital and analog electronics design. The digital section provides the necessary customization for production-tolerance-induced variations in the helmet components and provides discrete control functions whose exact settings can be reproduced on command. The analog section provides the signal processing and amplification at speeds where digital technology either cannot compete or is inappropriate. As already mentioned during discussion of the CRT wiring harness, some of the helmet

electronics functions may be distributed, and thoughtful design will take advantage of performance advantages that are already available.

DIGITAL SUBSYSTEM FEATURES

The digital subsystem usually incorporates an embedded processor and associated digital functions that implement data processing and data transfer between itself and external destinations that provide the necessary adjustment of the system's analog parameters. The register length or number of bits required to provide optimal adjustment of each display system parameter varies as a function of the parameter's dynamic range and required resolution. Often standardized register lengths simplify design and programming activities. Then, the worst case parameter, usually focus voltage control, dictates register length. A variable focus control can have a range of 2000 volts (1000-3000 volts absolute). Under the HMD's magnification, a volt or two of change from optimum can often be observed as a defocusing of the CRT image. Thus, unless offsets are used around a presumed operating point, a register length of 10 to 12 bits might be optimum. At least four major operational functions normally benefit from digital control or adjustment capability.

1. Due to the manufacturing practices now prevalent for CRTs, their optimum operating parameters, meaning the settings of its grid control voltages, can vary over a significant range. With digital control, optimum CRT operating parameters can either be read from serial programmable read-only memory (PROMs) sometimes provided with each CRT and its interconnect, or loaded into the processor's associated memory for use when a particular CRT is selected to operate with the electronics.

2. As mentioned earlier, some form of geometry mapping of the CRT's format into HMD optical space is required for most HMDs. While analog multipliers normally still perform the signal multiplication process, variations between HMDs make it convenient to provide registers that can be loaded with digital values representing the magnitude of each needed correction term's coefficient.

3. Some displays, particularly binocular displays, and especially binocular displays with partial overlap, may require alignment patterns to aid the operator in performing the final electronic alignment of each eye's image to form what appears to be a single contiguous image. These alignment patterns are normally configured for a specific HMD, and are best implemented as preprogrammed representations in some variant of nonvolatile memory for recall, as needed.

4. Control panel adjustments are often made for specific conditions. Digital control through the control panel usually means that adjustments can also be saved or input for the operator if known conditions have either been recorded for subsequent use or can be determined by some automated system and entered for the operator without his direct interaction. This often becomes a useful feature, especially when multiple inputs are being multiplexed for simultaneous display on the HMD and desired relative settings for each source's information is known.

ANALOG SUBSYSTEM FEATURES

The display electronics analog video processing section usually acts as the direct signal path for the video and deflection signals. It also implements signal processing functions best performed in the analog domain. Some major operational functions that may be considered for inclusion as part of the analog system's functions are listed below.

1. For most helmet display electronics, geometry correction, its purpose already mentioned in the CRT section, is usually implemented using analog multipliers and imbedded in the geometry correction portion of the deflection circuitry .

2. A larger CRT image requires less magnification by the optics. Since the exit pupil diameter for the HMD is the relay lens (more properly, objective lens) effective aperture divided by magnification, the relay lens can have a smaller diameter, i.e., a higher f-number. This makes it smaller, lighter, less expensive, and, possibly, of higher optical quality. To reduce the required magnification, and therefore working f-number of the HMD optics, the image is usually overscanned in the horizontal direction to also enlarge the vertical height of the display format for a given aspect ratio. If this requirement and any rotations or translations of the CRT's format force the scanned area to move off the phosphor quality area of the CRT, the CRT must be protected from thermal damage. A process known as circular blanking is used to blank (turn-off) the beam when it reaches predefined limits at the edge of the phosphor quality area. (See Reference 3)

3. For HMDs with partially overlapped fields of view, specially circuitry is sometimes added to roll-off the beam intensity in the overlap area to maintain relatively uniform luminance conditions across the entire displayed image.

4. Many of today's high resolution, high luminance miniature CRTs often exhibit distinct nonlinearities in their luminance gray shade profiles. This condition is usually most noticeable with the brightest gray shades. To allow the CRT luminance function to be corrected to a more linear and desirable luminance function, programmable gamma correction is sometimes included.

5. If separate line rates are to be used with the display electronics, then the raster generation process must be able to accomplish stable switching between these different rates. To support multiple video input options, each deflection channel usually must incorporate separate multi-rate raster generators for each source. These permit switching between raster sources having different rates. When changing between rates, the display electronics sweep generators must eliminate size adjustments with automatic size control that could lead to bothersome problems for the user of the display. Achieving multisync performance over the larger deflection bandwidths required of some HMD applications has usually been accomplished with some significant limitations.

6. VCS applications often require that the imagery displayed on the HMD be stabilized with respect to a coordinate frame other than the head while the head is moving about the cockpit or crew station. Depending upon the HMD configuration, proper stabilization requires either a pure rotation or a combination of a rotation and translation of the display imagery as the head/helmet moves. The head -racking signals needed to perform the calculations for the imagery stabilization normally must be obtained through a high speed serial bus (See Figure 4-21) connected between the display electronics and a helmet orientation and position tracking system. Usually, the display electronics supports this requirement only for raster based imagery. Stroke imagery must be rotated and translated at its source.

7. As explained earlier in the discussion concerning the CRT image source, the CRT is a tangent (theta) mapped system, while most HMDs obtain maximum optical performance and minimum weight using F(theta) mapped optical designs. Specific optical designs, whether they are monocular or binocular, may have other types of distortion that must be compensated for by nonlinear mapping of the CRT image. Finally, the CRT, itself, may have internal distortion requiring correction due to the interaction of the deflection yoke, electron gun and e-beam. Given the magnitude and types of distortion associated with HMDs, even-order compensation, up to fourth order terms, would be desirable. However, signal-to-noise considerations in the HMDE electronics effectively limit the geometric correction to third order terms. Thus, approximations must sometimes be made for a given optical system, but the correction obtained is usually sufficient in subjective terms relating to viewer comfort, if not in terms of the absolute mapping coordinates.

SYSTEM and POWER SUPPLY PERFORMANCE

Performance values for a representative miniature display electronics are shown in Table 4-12. The ability to obtain the needed performance is, in turn, dependent upon the specification of a reasonable set of CRT voltages, adjustment ranges for those voltages, and the maximum operating currents that are allowed. Table 4-13 provides a set of specifications for the latest CRT designs that provide operating margins which permit minimal power supply noise and regulation requirements to be met.

The FUTURE

The development course of the display electronics is very difficult to predict. It will, of course, be determined largely by the types of image sources that are dominant for HMD applications and the resolution demands of sensor and computer-generated-imagery. Digital technology should continue to make inroads regardless of the type of image source that is used. If CRTs remain dominant, then, at a minimum, the electronics' designs will take advantage of the recent developments in the wiring harness and its incorporation of portions of the CRT's electronic interfaces.

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FIGURE 4-1
ALTERNATIVE IMAGE SOURCE TECHNOLOGIES

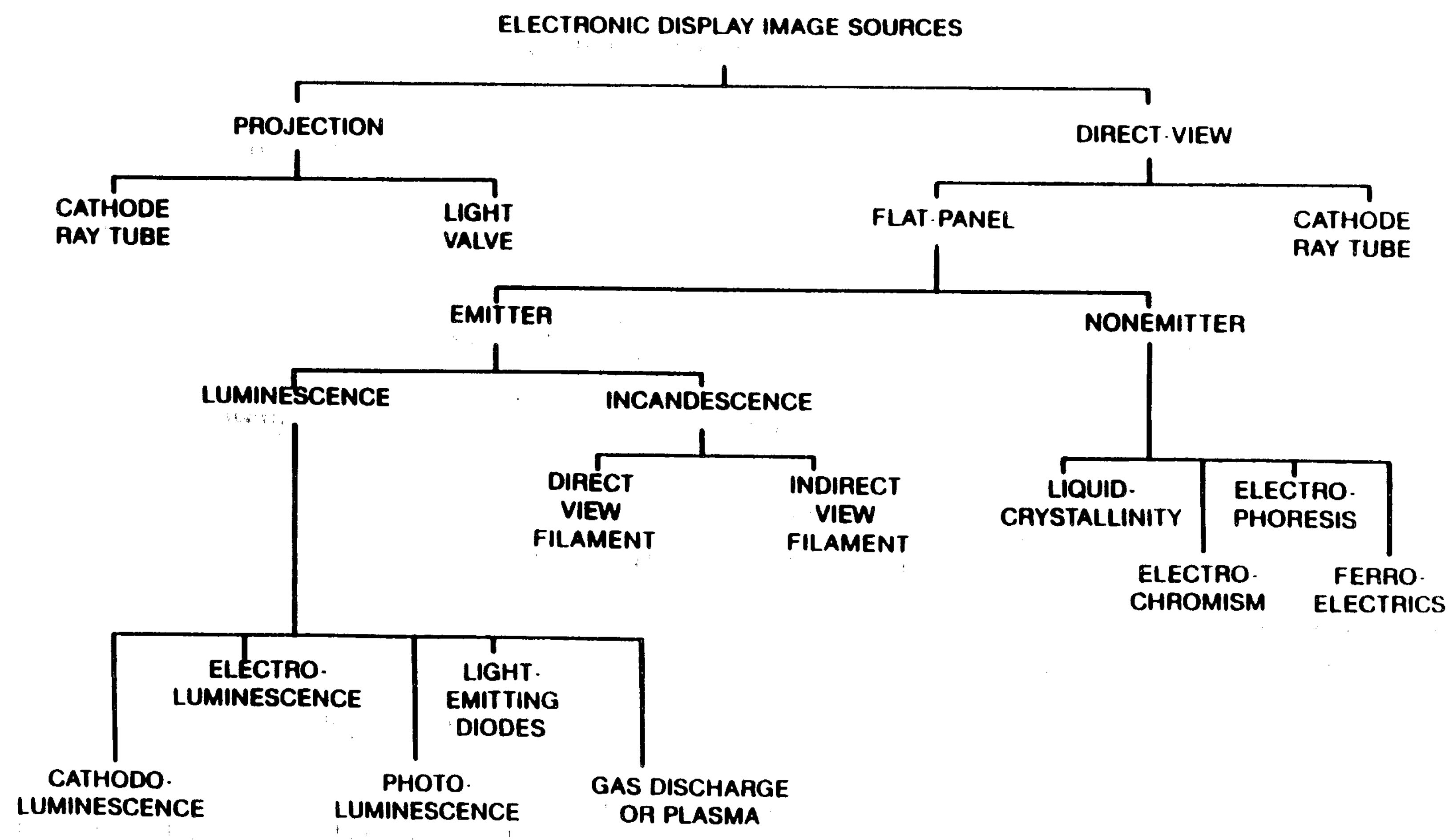

TABLE 4-1
CRT PERFORMANCE CHARACTERIZATION BY PHOSPHOR AREA FORMAT SIZE

CRT Parameter	Format Size: 6mm	12mm	16mm	19mm	23mm
1) Approximate diameter	15mm	18mm	23mm	27mm	30mm
2) Length range	50-55mm	65-80mm	110-120mm	100-120mm	135-145mm
3) Weight*	12-18grams	35-45grams	85-100grams	85-160grams	120-140grams
4) Final acceleration potential	~6kV	~9kV	~11kV	~13.5kV	~13.5kV
5) Deflection method	Magnetic	Magnetic	Magnetic	Magnetic	Magnetic

*Assumes 6" of leads

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FIGURE 4-2
MINIATURE CRT TYPES FOR HMDs

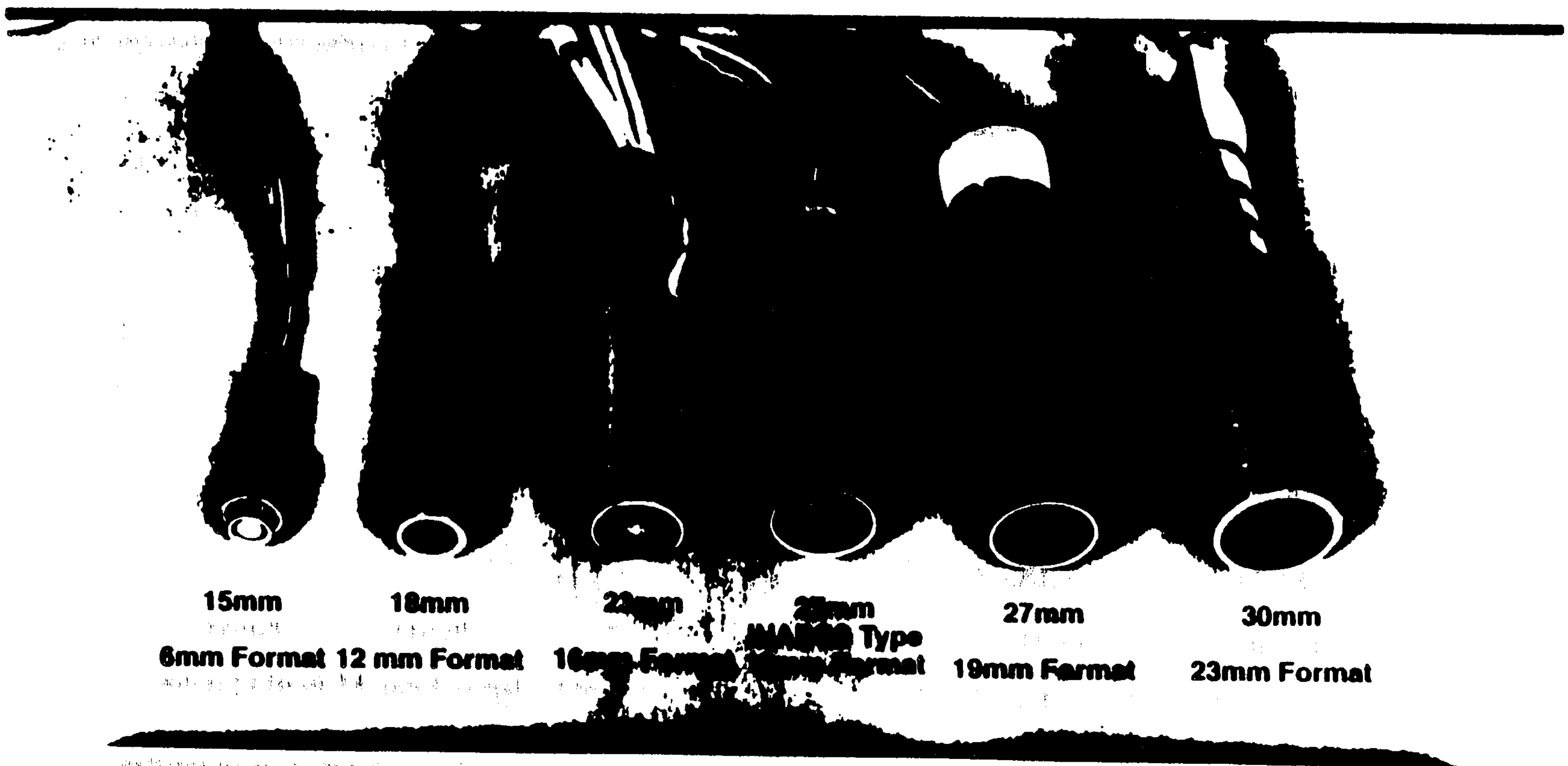


TABLE 4-2
PHOSPHOR / FACELPLATE TYPES

Item	Types
Faceplate	FOB Glass Sapphire
Phosphor	Particulate Sputtered Single-Crystal

DFK-92-3-16

TABLE 4-3
REPRESENTATIVE MINIATURE CRT DEFLECTION YOKE TYPES

Parameter	Performance Categories: Low μH	Performance Categories: High μH
Inductance*		
Horizontal	14-16 μHenries	110-125 μHenries
Vertical	19-21 μHenries	140-155 μHenries
Resistance*		
Horizontal	0.45-0.50 ohms	1.5-1.6 ohms
Vertical	0.45-0.55 ohms	1.7-1.8 ohms
Capacitance*		
Horizontal	50-60 picofarads	?
Vertical	55-65 picofarads	?

*Assumes 48" twisted pair leads

DFK-92-3-13

FIGURE 4-3
DISPLAY REQUIREMENT IMPACT ON IMAGE SOURCE PERFORMANCE

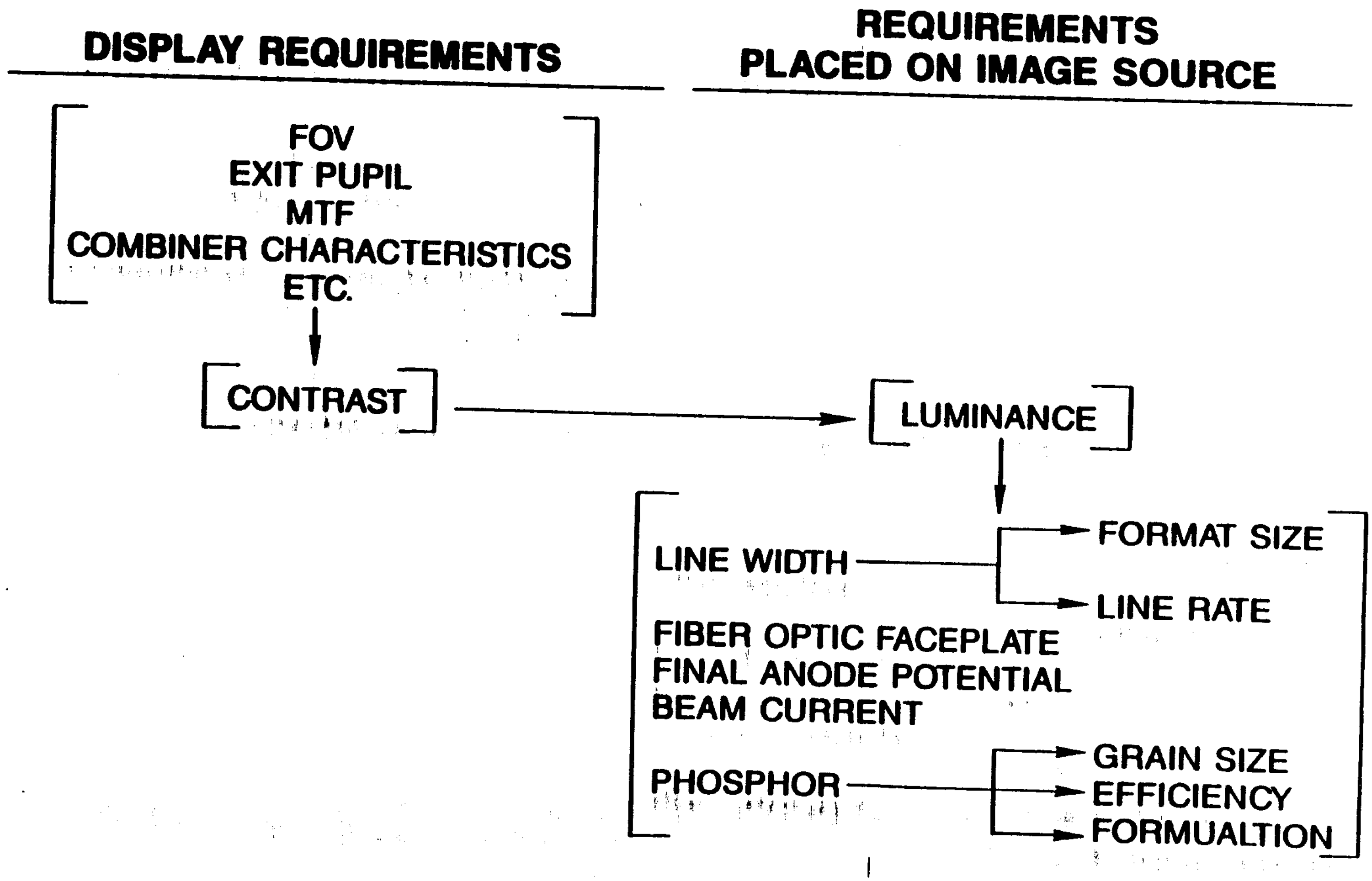
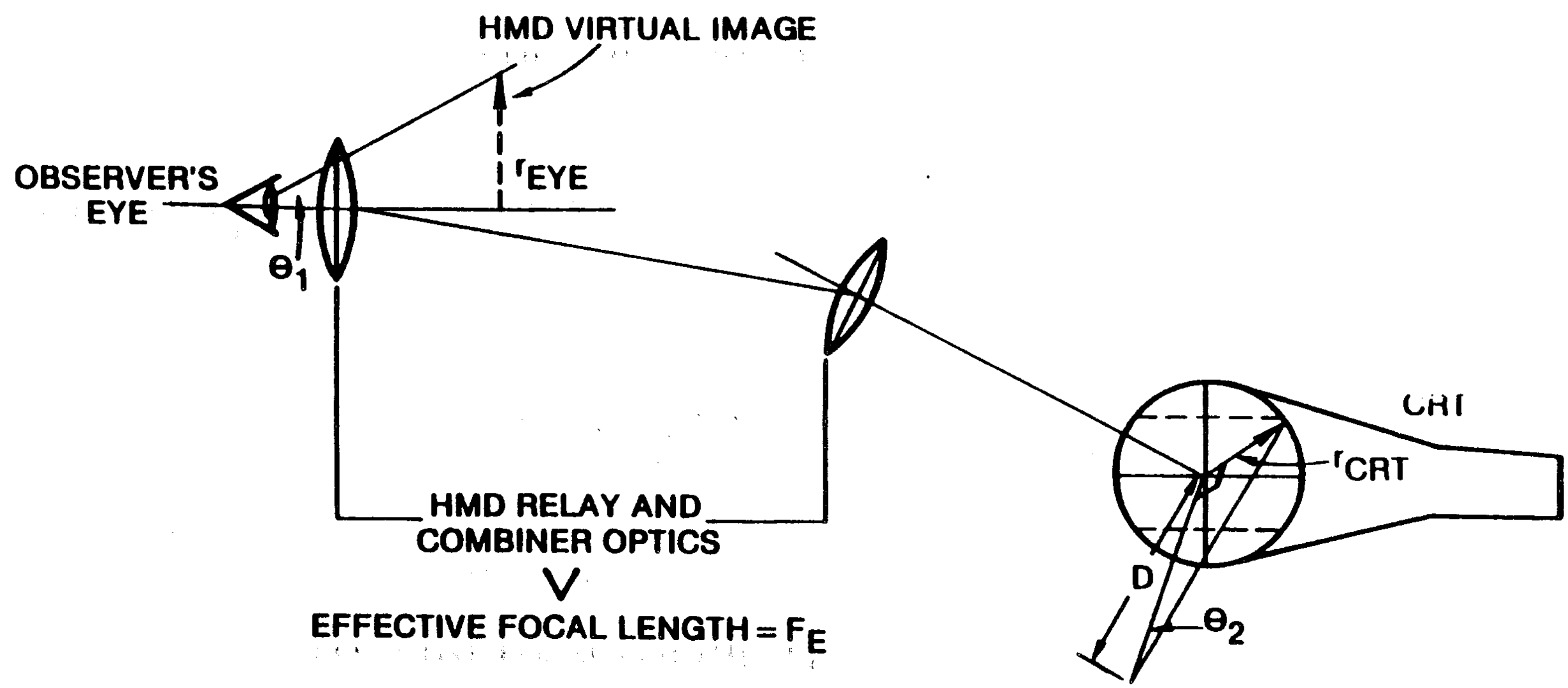


FIGURE 4-4
CRT/OPTICS MAPPING COMPENSATION



EFFECTIVE FOCAL LENGTH = F_E

F(Θ) MAPPED OPTICS $\Longrightarrow$ $r_{EYE} = F_E(\Theta_1)$; WHERE Θ_1 HAS UNITS OF RADIANS

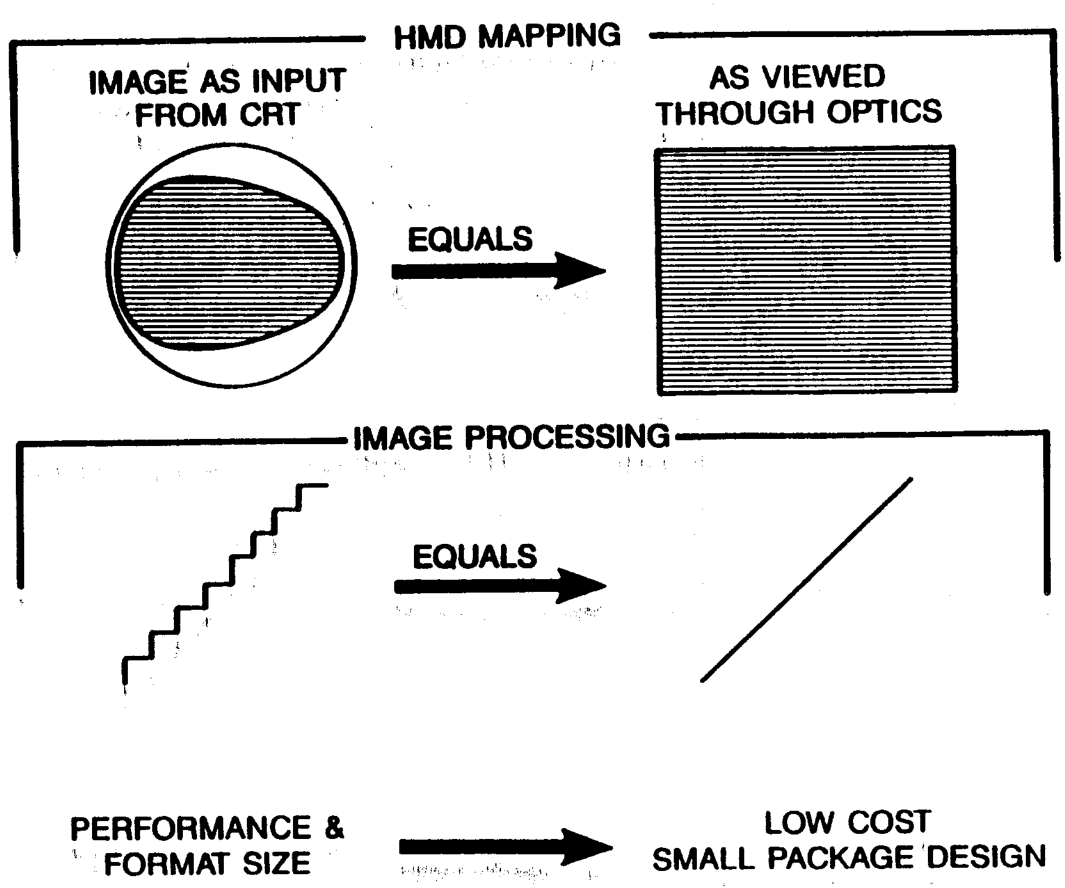
F – TAN (Θ) MAPPED CRT $\Longrightarrow$ $r_{CRT} = D\,(TAN\,(\Theta_2))$

IF NO DISTORTION PRESENT THEN $\Theta_1 = \Theta_2$

THEREFORE $r_{EYE} = F_E(ARCTAN\,(\frac{r_{crt}}{D}))$

HE-88-2 18

FIGURE 4-5
THE MINIATURE CRT (WHY?)



DFK-91-4-15

TABLE 4-4
MAJOR PERFORMANCE LIMITING PROBLEM AREAS FOR MINIATURE CRTS

CRT FACEPLATE SYSTEM	ELECTRON OPTICS	OTHER PROBLEMS
MAINTAIN HIGH LUMINOUS EFFICIENCY DURING ALL CRT DRIVE CONDITIONS MINIMIZE PHOSPHOR'S CONTRIBUTION TO BEAM SPREADING/LINE WIDTH IMPROVE CONTRAST	ELECTRON OPTICS CAPABLE OF FOCUSING SMALL BEAM DIAMETER AT HIGH BEAM CURRENTS THERMAL LIMITATIONS SPACE CHARGE SPREADING ABERRATIONS	ACCELERATION VOLTAGE CRT's PHYSICAL SIZE MAGNIFICATION GETTERING DEFLECTION YOKE PERFORMANCE CATHODE LOADING

FIGURE 4-6
REPRESENTATIVE EMD / ESFL BIPOTENTIAL LENS MINIATURE CRT

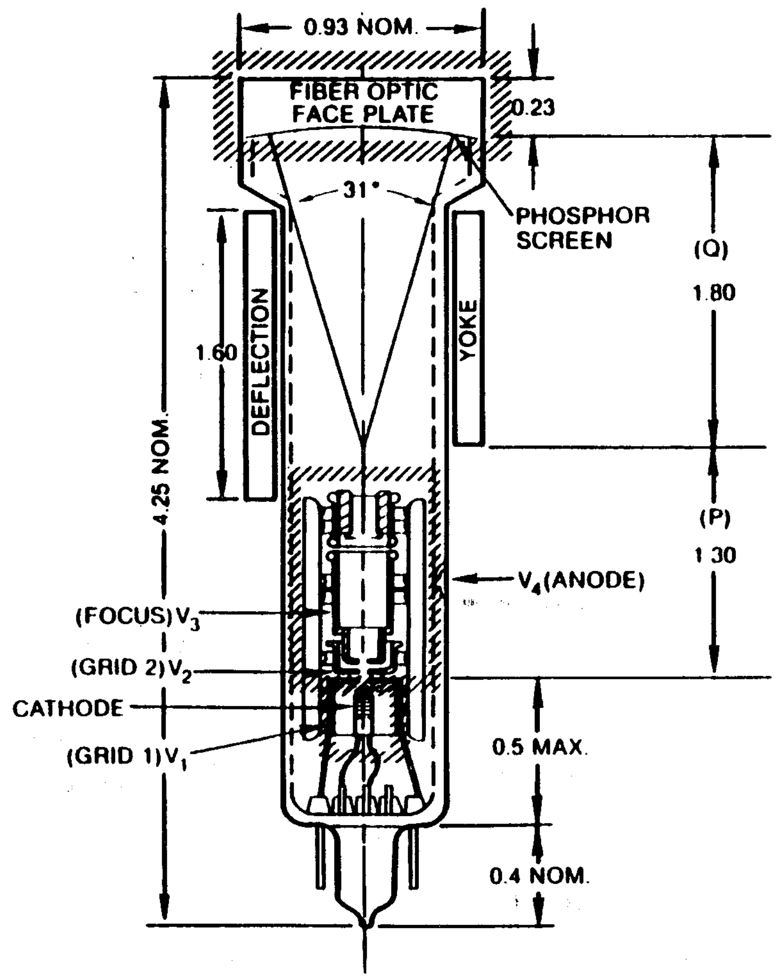


TABLE 4-5
CATHODE LOADING
AND G_1 APERTURE SIZE

Dg1	PEAK CATHODE LOADING vs 70V DRIVE CONDITION	
	100% DUTY CYCLE	50% DUTY CYCLE
10 MILS	8.4 A/cm^2	4.2 A/cm^2
13 MILS	5.0 A/cm^2	2.5 A/cm^2
15 MILS	3.75 A/cm^2	1.9 A/cm^2

Table 4-6
Test Results for Recent Bipotential Lens Gun CRTs

Refresh Rate (Cycles/Sec)	Luminance Level (Ft-Lamberts)	CRT Serial Number	Drive Voltages (Volts)	50% Linewidth (Mils)	Beam Current (Microamps)	Luminous Efficiency (Lumens/watt)
120	17,000	31261	62.0	0.956/1.37	140	16.5
		32162	53.2	1.23/1.62	140	21.3
		32163	63.0	1.17	190	14.9
240	17,000	32161	45.3	0.903/1.30	68	16.4
		32162	38.9	1.15/1.57	65	21.4
		32163	47.2	1.13	81	16.9

CRT Type: Hughes 1473   Test Conditions: 13kV, 30k inches/sec, 17 x 12.75mm Format

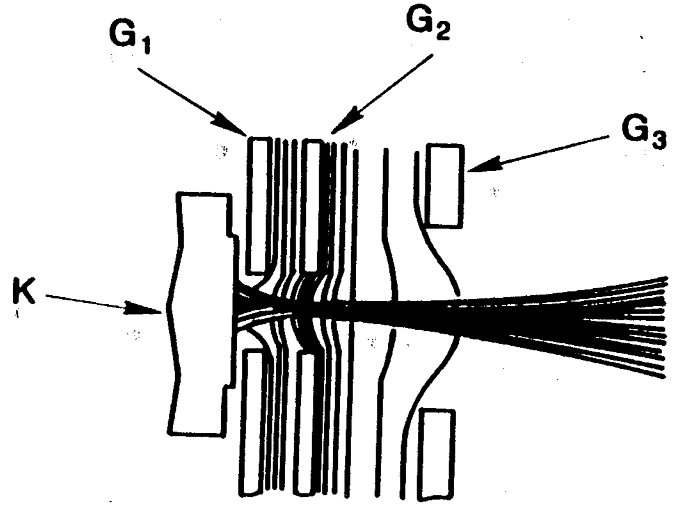
Table 4-7
Test Results for Recent Bipotential Lens Gun CRTs

Refresh Rate (Cycles/Sec)	Luminance Level (Ft-Lamberts)	CRT Serial Number	Drive Voltages (Volts)	50% Linewidth (Mils)	Beam Current (Microamps)	Luminous Efficiency (Lumens/watt)
120	13,200	32159	75	1.14	190	9.5
	12,750	32160	?	1.0	150	11.3
240	17,000	32159	63	1.05	80	14.9
	17,000	32160	63.5	1.05	83	13.8

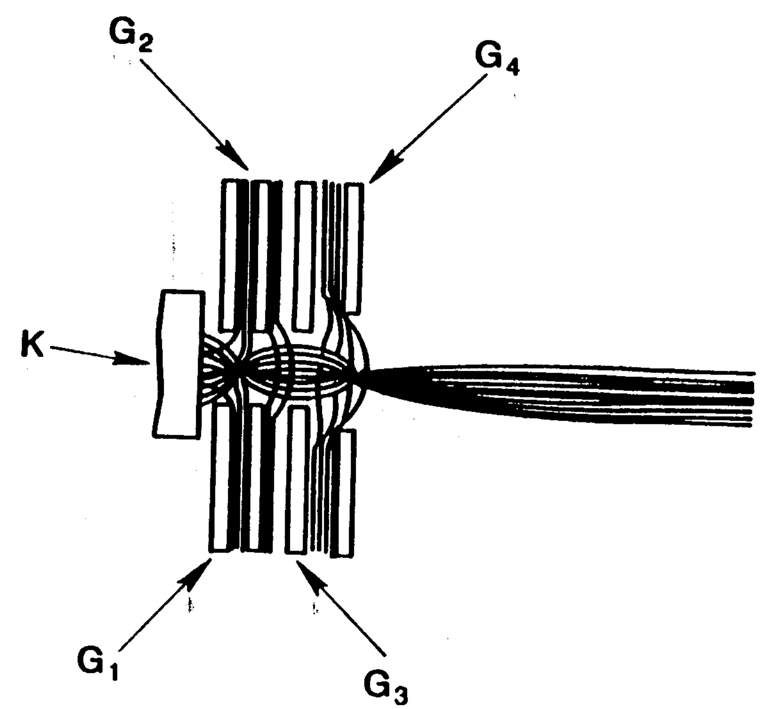
CRT Type: Hughes 1473 Test Conditions: 13kV, 30k inches/sec, 17 x 12.75mm Format

FIGURE 4-7
ADVANCED CRT ELECTRON GUNS

CONVENTIONAL BIPOTENTIAL LENS BFA



DECELERATOR PRE-FOCUS LENS (DPFL) BFA



NOTE: BFA = BEAM FORMING ARFA

Table 4-8
Recent Results With New DPFL Gun CRTs

Refresh Rate (Cycles/Sec)	Luminance Level (Ft-Lamberts)	CRT Serial Number	Drive Voltages (Volts)	50% Linewidth (Mils)	Peaks Cathode Loading ($Amps/cm^2$)
60	~8300	90-35122	63.5	~1.0	4.32
	~7000	90-35123	69	~1.15	4.90
120	17,000	90-35122	63.5	1.01/1.04	4.32
		90-35123	6.90	1.05/1.07	4.90
240	17,000	90-35122	41.2	0.98/1.00	2.26
		90-35123	44.8	1.01/1.04	2.56

CRT Type: Hughes 1475   Test Conditions: 13kV, 30k inches/sec, 17 x 12.75mm Format

FIGURE 4-8
DISPENSER CATHODE

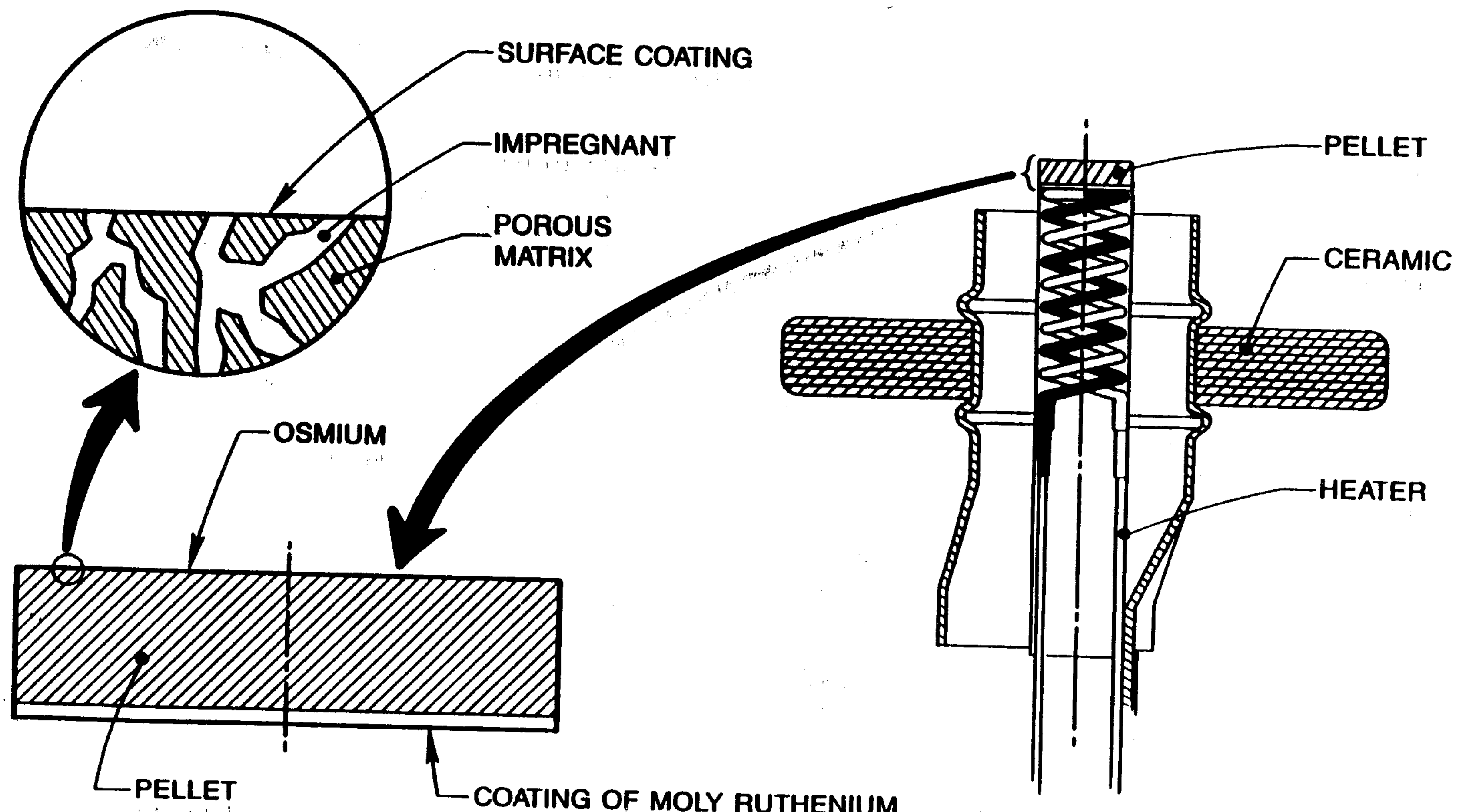
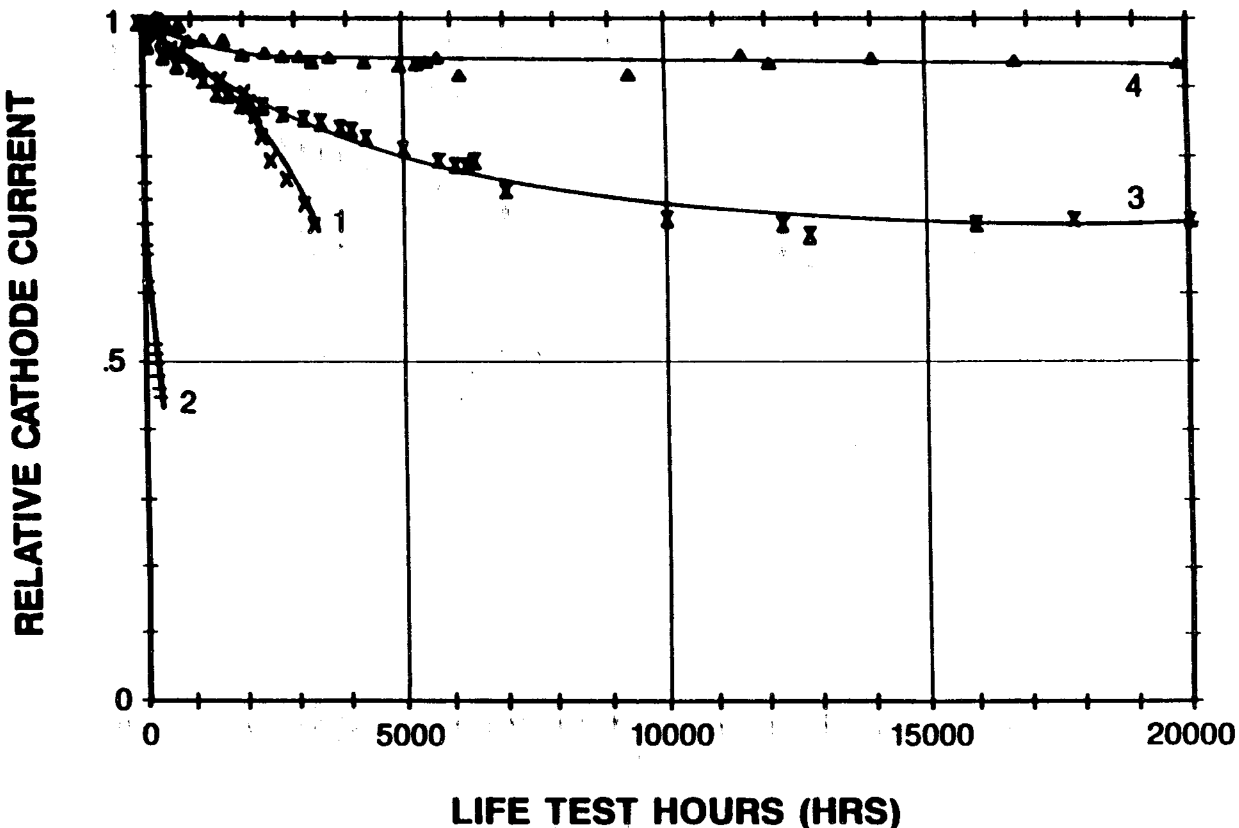


FIGURE 4-9
DISPENSER vs OXIDE CATHODE PERFORMANCE



CURVE 1 : OXIDE CATHODE AT 1 A/cm^2
CURVE 2 : OXIDE CATHODE AT 5 A/cm^2
CURVE 3 : B TYPE DISPENSER CATHODE AT 5 A/cm^2
CURVE 4 : M TYPE DISPENSER CATHODE AT 5 A/cm^2

FIGURE 4-10
FIELD EMITTER ARRAY CATHODE

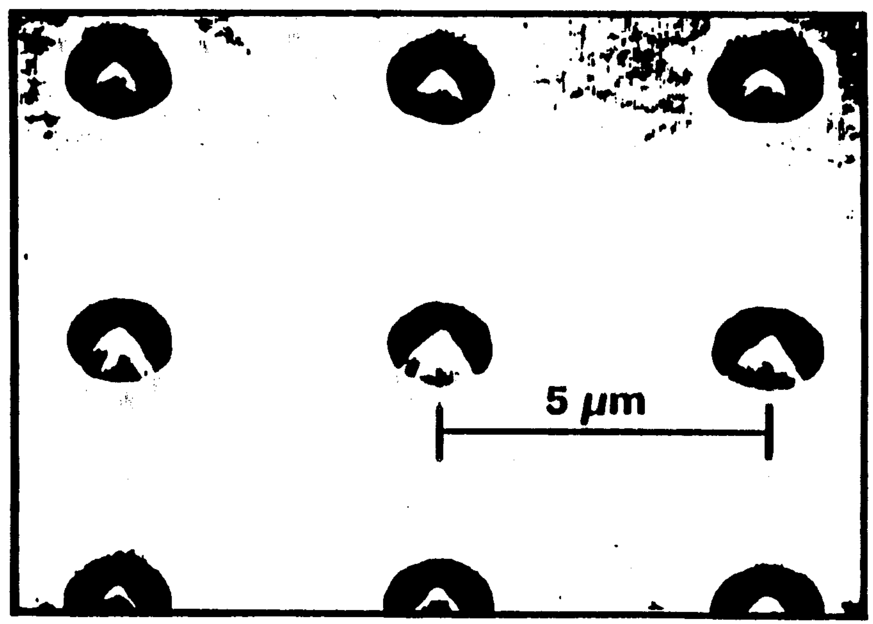


FIGURE 4-11
COMPARISON OF MINIATURE CRT PERFORMANCE IMPROVEMENTS

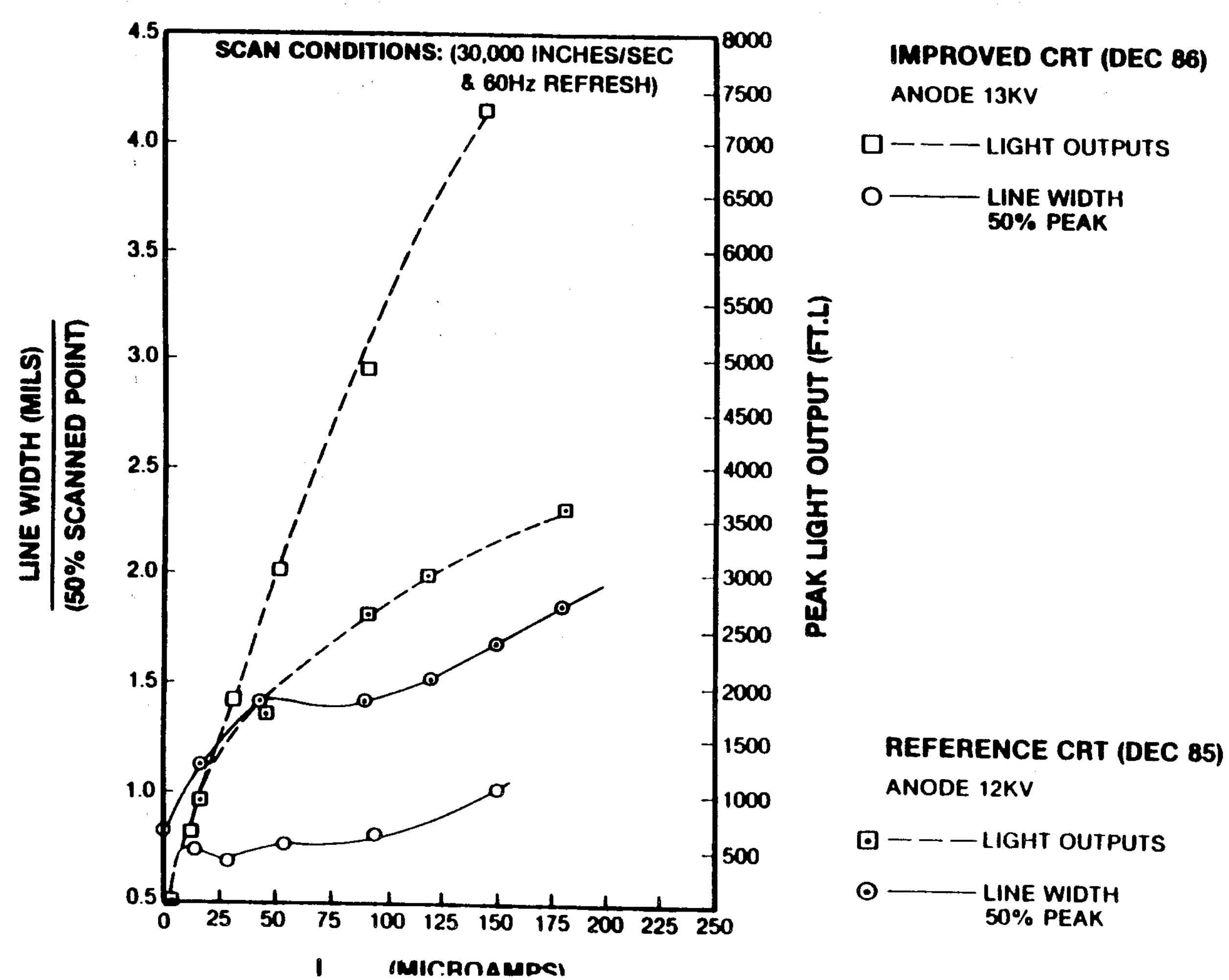


FIGURE 4-12
LINE WIDTH MEASUREMENTS WITH 1″ CRTs

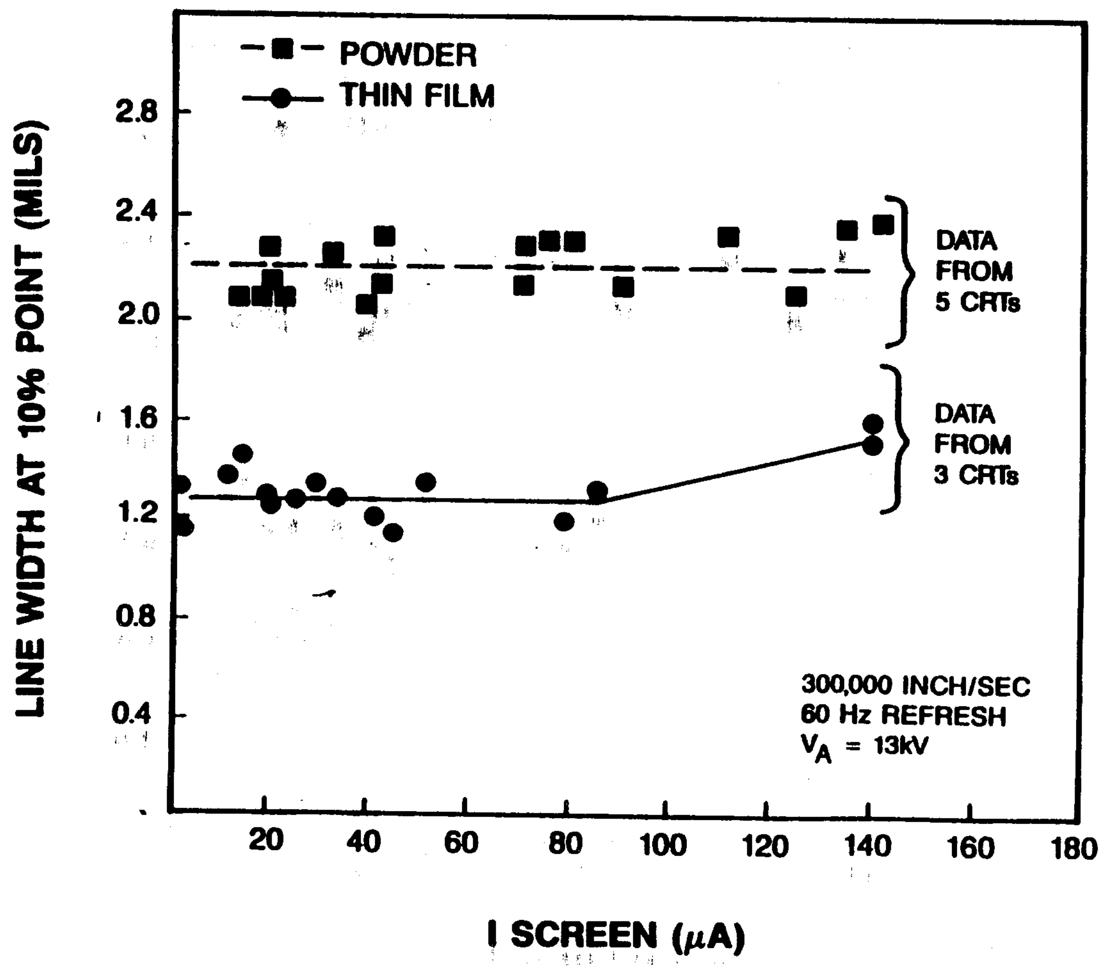


FIGURE 4-13
INTAGLIATED PHOSPHORS

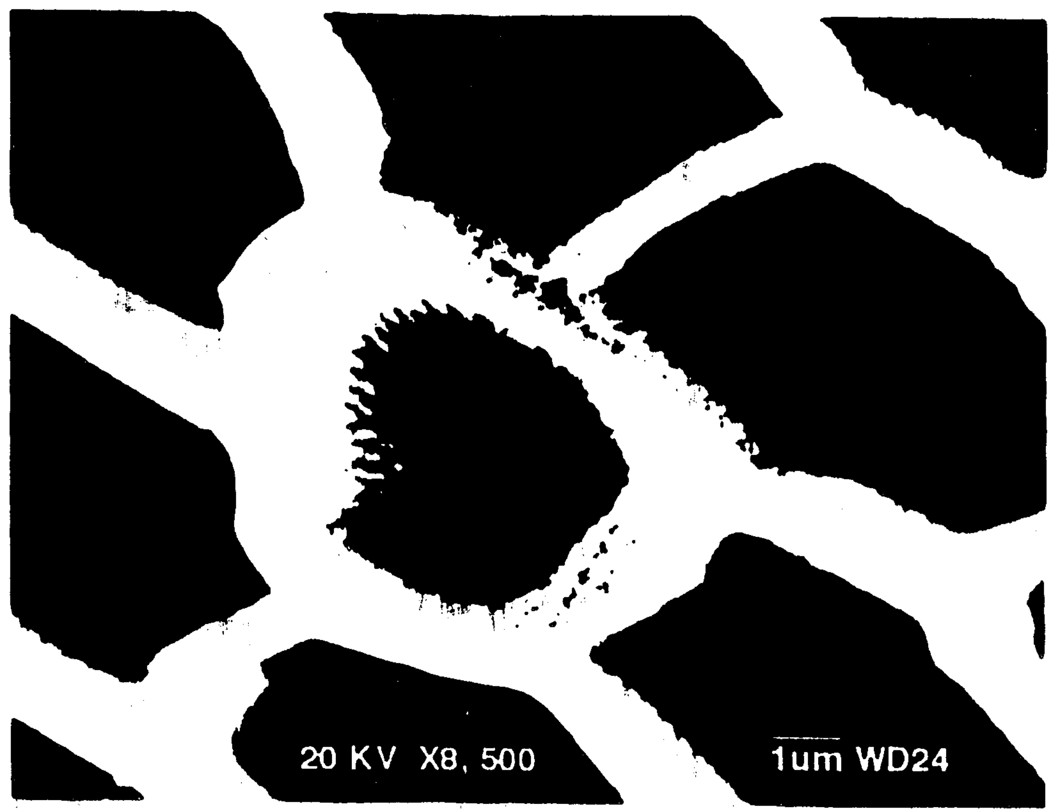


FIGURE 4-14
MINIATURE COLOR DISPLAY SCHEMATIC

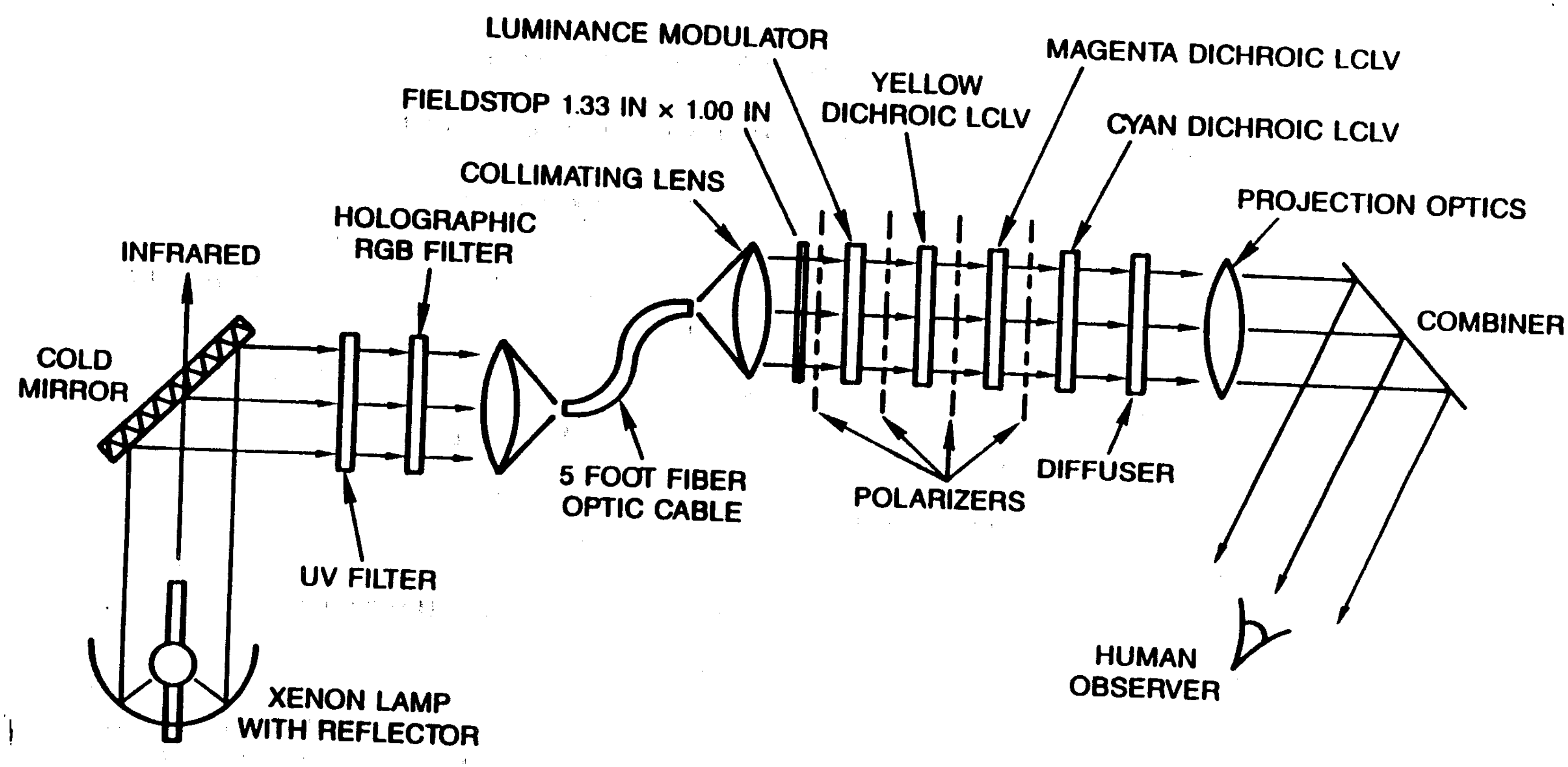


FIGURE 4-15
MINIATURE COLOR DISPLAY HMD CONCEPT

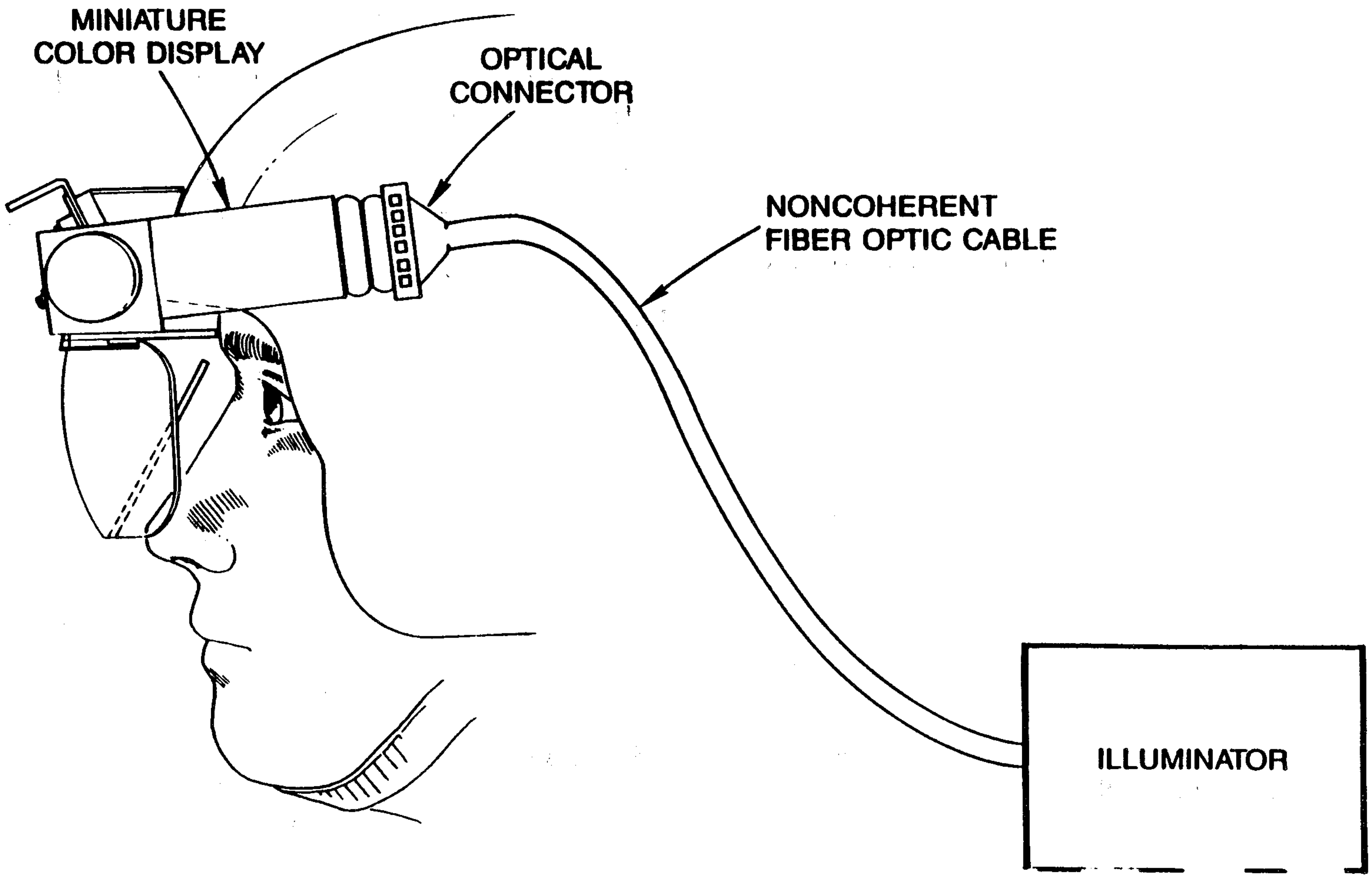
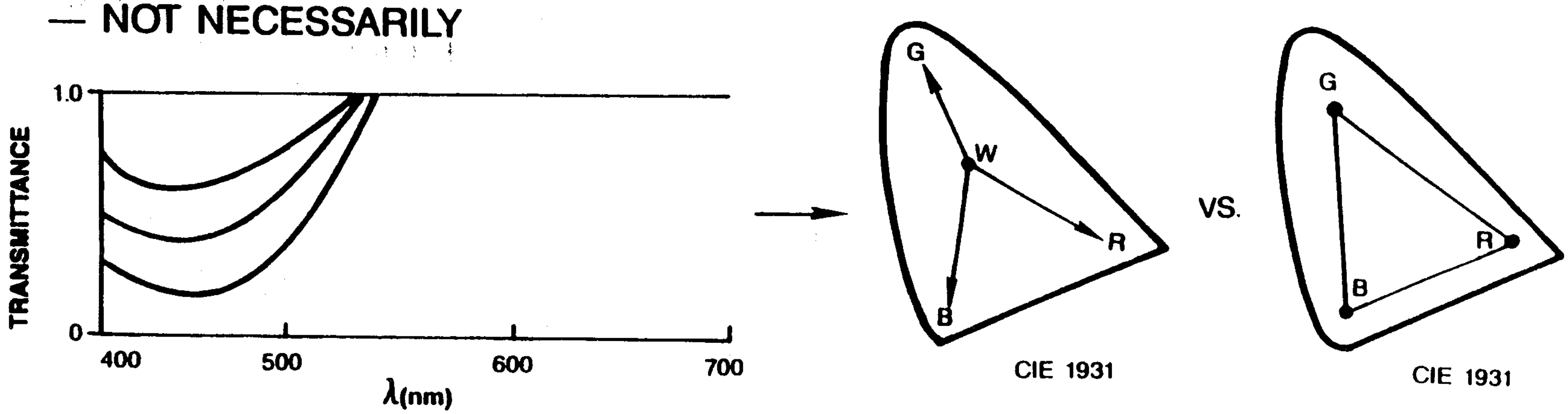


FIGURE 4-16
SUBTRACTIVE COLOR LCD IMAGE SOURCE

COLORMETRIC PITFALL #1

ADDITIVE
— CHROMATICITY OF R, G, B PRIMARIES IS INVARIANT

SUBTRACTIVE
— NOT NECESSARILY



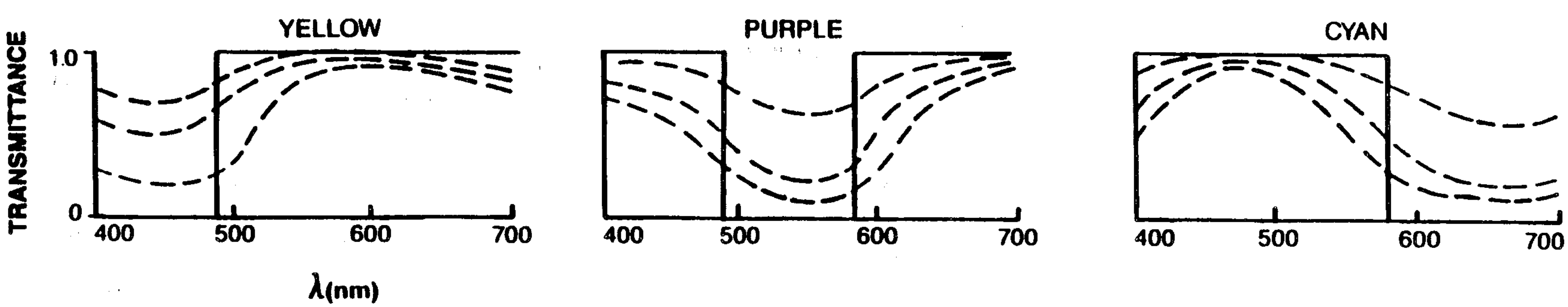
CONCLUSION
— IF A BROADBAND ILLUMINANT IS USED, THE CHROMATICITIES OF THE PRIMARIES WILL BE F(LUMINANCE)

FIGURE 4-17
SUBTRACTIVE COLOR LCD IMAGE SOURCE

COLORMETRIC PITFALL #2

ADDITIVE
— R, G, B PRIMARIES DO NOT INTERACT

SUBTRACTIVE
— NOT NECESSARILY



CONCLUSION
— USE OF AN ILLUMINANT CONTAINING ONLY THREE WAVELENGTHS, SUITABLY POSITIONED, CAN MINIMIZE OR ELIMINATE CROSSTALK

TABLE 4-9
Requirements Being Considered for Implementing a QDC and Wiring Harness Assembly

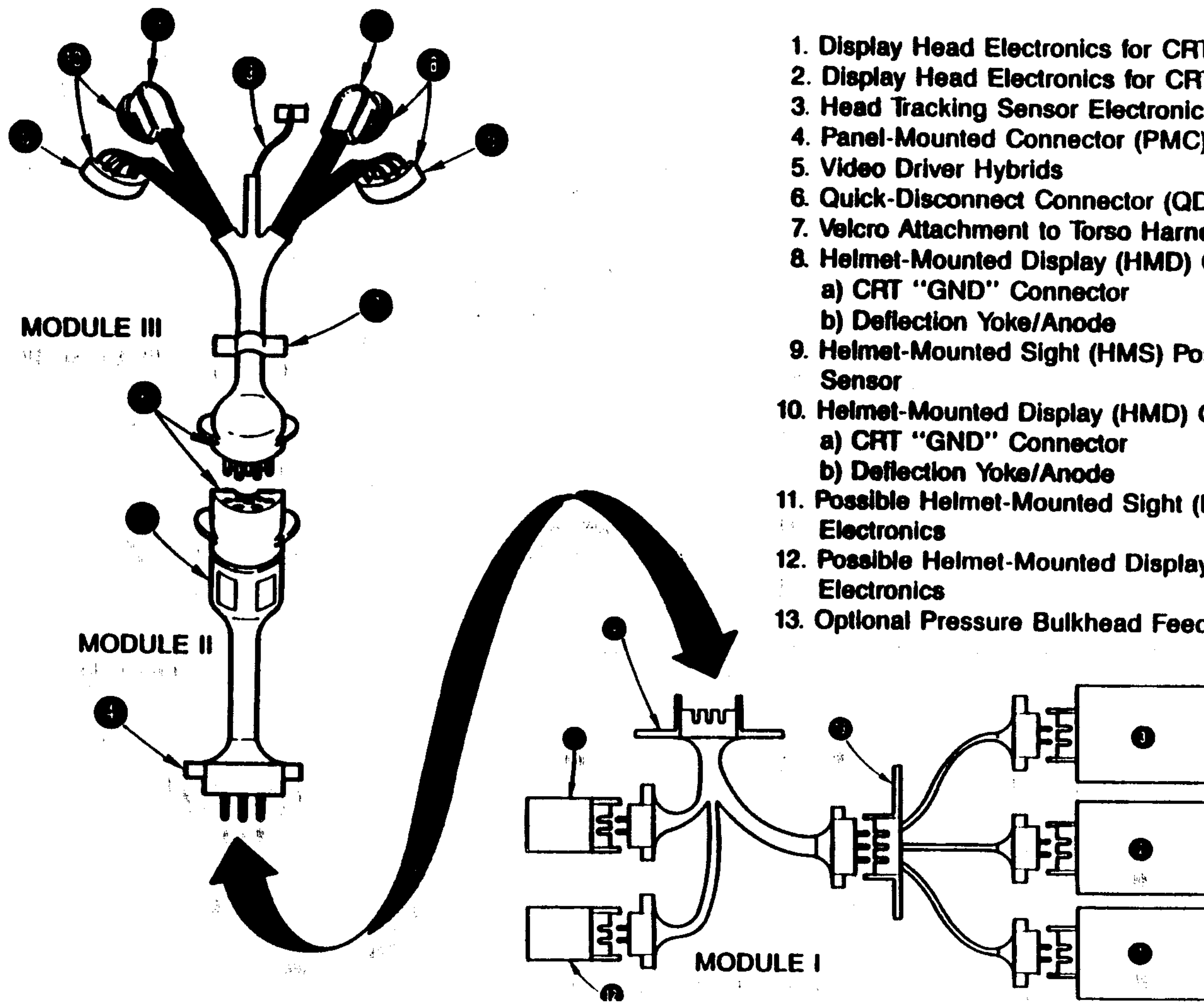
Item	Description
1.	The interface system must be capable of handling voltages up to 13,500 volts.
2.	The interface system must transmit video signals, maintaining a bandwidth on the order of 70 megaHertz.
3.	The video and deflection leads must minimize distributed capacitance. This requirement will help minimize signal loss for the video and maintain the deflection yoke system resonant frequency for adequate deflection system step response and settling times. This, in turn, will help minimize drive requirements for the final video and deflection amplification stages.
4.	The QDC must be explosion proof during rapid egress in an explosive vapor or gas environment.
5.	The QDC must separate without pilot intervention with a linear pull force of 12 to 20 pounds exerted in a rapid egress situation.
6.	The connector must disconnect "hot" (power on) without exposing any arc or hot ember to the cockpit environment.
7.	"Hot" separations shall not cause damage to the electronics or other parts of the system.
8.	The disconnect must be capable of reconnecting "hot" without damage to the system. As a partial alternative the cable may provide a relay signal interconnect which triggers electronic crowbaring of the electronics upon QDC separation and triggers electronics "turn-on" during reconnecting.
9.	The QDC shall be torso mounted.
10.	The QDC shall provide the functional everyday interface between the pilot and aircraft with power off.
11.	The hybrid video drivers shall be attached to the QDC or its backshell. See section on their performance which immediately follows this section.
12.	The system shall be designed as three or four separate modules to facilitate maintenance, testing, repair and replacement. These modules are defined as: a) the interconnect from the aircraft electronics to the PMC, b) the interconnect from the PMC to the QDC, c) the interconnect from the QDC to the helmet mounted devices, and d) the optional fourth module where pressure feed-through is required.
13.	The QDC Assembly must be flightworthy and safe.
14.	The QDC assembly must function without heating the cables. Shielding effectiveness and resistivity changes due to temperature changes must be minimized.
15.	The QDC assembly must function without significant attenuation of its signals.
16.	Crosstalk between the high and low voltage leads shall be minimized.
17.	The shape, size, and weight of the QDC shall be optimized so that it remains unobtrusive on the aviator's torso and poses no inconvenience to normal maneuvers.
18.	There shall be no dangling cables in the path of the aviator in an ejection situation.
19.	The electronics at either end must be protected from power surges resulting from hot disconnect or re-connection of the QDC.
20.	The QDC explosion proofing requirement shall apply up to an altitude of 15,000 feet above sea level, to support safe ground egress for the voltage levels shown .

TABLE 4-10

Requirements Being Considered for Implementing a QDC and Wiring Harness Assembly

Item	Description
21.	The upper cable module interfacing to the helmet shall be designed for maximum flexibility.
22.	The QDC shall remain completely functional after 100 hot disconnects and 100 hot mating cycles.
23	The QDC shall separate with a linear pull of less than 24 pounds when the separation pull is applied at an angle of up to 30 degrees relative to the disconnect centerline.
24.	The QDC shall separate when the emergency egress pull force is applied at a velocity of up to 325 inches per second. The separation force shall not exceed 20 pounds for more than 0.3 milliseconds.
25.	The disconnect shall withstand +9 G's of acceleration for 60 seconds without damage or loss of function.
26.	The helmet to upper QDC modular cable assembly shall be retained to the pilot so as not to cause harm to the wearer during an ejection and in windblasts up to 600 knots. (subject to design of oxygen-mask-to-helmet connector)
27.	The mated cable and QDC assembly shall function at rated voltages when subjected to 100% humidity with cycling over the temperature range of -55°C to 70°C.
28.	The helmet to upper QDC modular cable assembly shall withstand 3000 traverse cycles of plus or minus 0.5 inch half amplitude of a point 6 inches from the helmet shell.
29.	The QDC shells shall establish a ground path prior to any contact engagement. The mated QDC shall exhibit a DC resistance of 2.5 milliohms or less from shell to shell.
30.	The disconnect shall withstand corona testing at rated specified voltages at 70,000 feet of altitude.
31.	The equivalent circuit parameters of the high voltage supplies and CRT must be established to determine if, in addition to the QDC, electronic crowbar circuitry is needed to provide an absolutely safe quick-disconnect under all operating conditions. (This may affect the design of the display electronics high voltage supplies, since separate outputs bypassing the supply's series output resistance may be needed.)

FIGURE 4-18
QUICK-DISCONNECT CONNECTOR WIRING HARNESS AND CONNECTOR(S)



1. Display Head Electronics for CRT 1
2. Display Head Electronics for CRT 2
3. Head Tracking Sensor Electronics
4. Panel-Mounted Connector (PMC)
5. Video Driver Hybrids
6. Quick-Disconnect Connector (QDC)
7. Velcro Attachment to Torso Harness
8. Helmet-Mounted Display (HMD) CRT 2 Connector
   a) CRT "GND" Connector
   b) Deflection Yoke/Anode
9. Helmet-Mounted Sight (HMS) Position/Orientation Sensor
10. Helmet-Mounted Display (HMD) CRT 1 Connector
    a) CRT "GND" Connector
    b) Deflection Yoke/Anode
11. Possible Helmet-Mounted Sight (HMS) Control Panel Electronics
12. Possible Helmet-Mounted Display (HMD) Control Panel Electronics
13. Optional Pressure Bulkhead Feedthru Connector

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FIGURE 4-19
AVVION CRT PLUG CABLE ASSEMBLY
STRAIGHT CONFIGURATION
MATED CONDITION

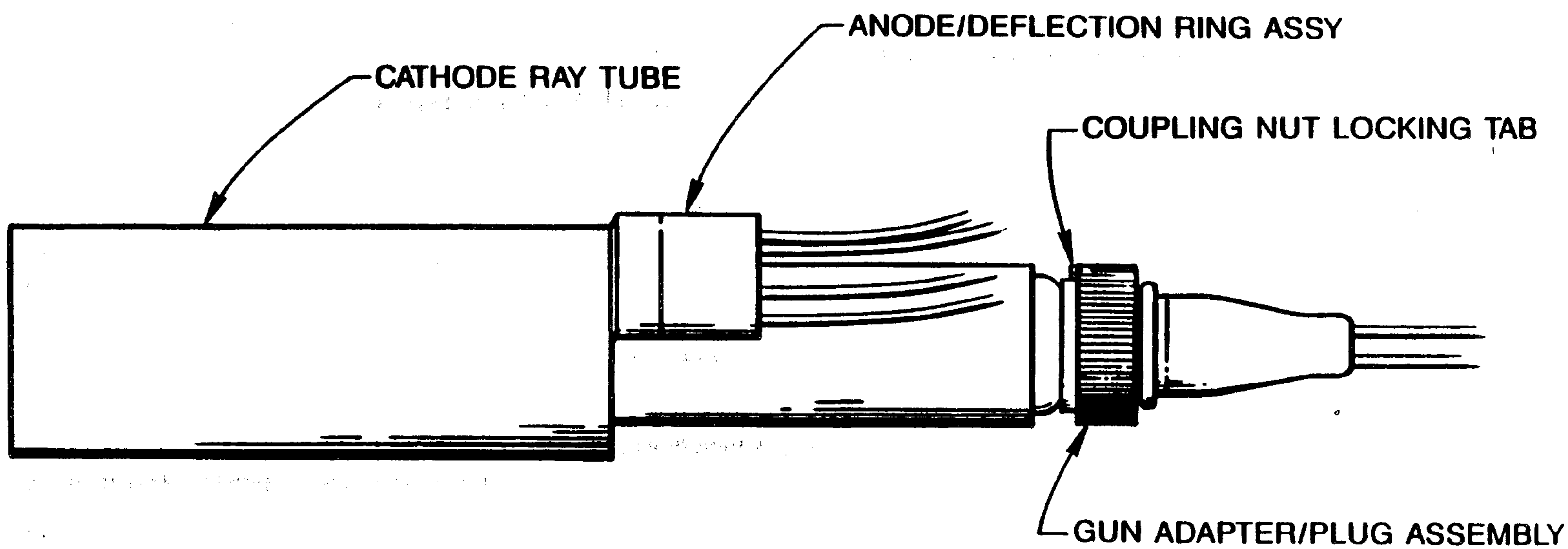

FIGURE 4-20
PIN CONFIGURATION AND NUMBERING FOR HIGH-VOLTAGE QUICK-DISCONNECT CONNECTOR

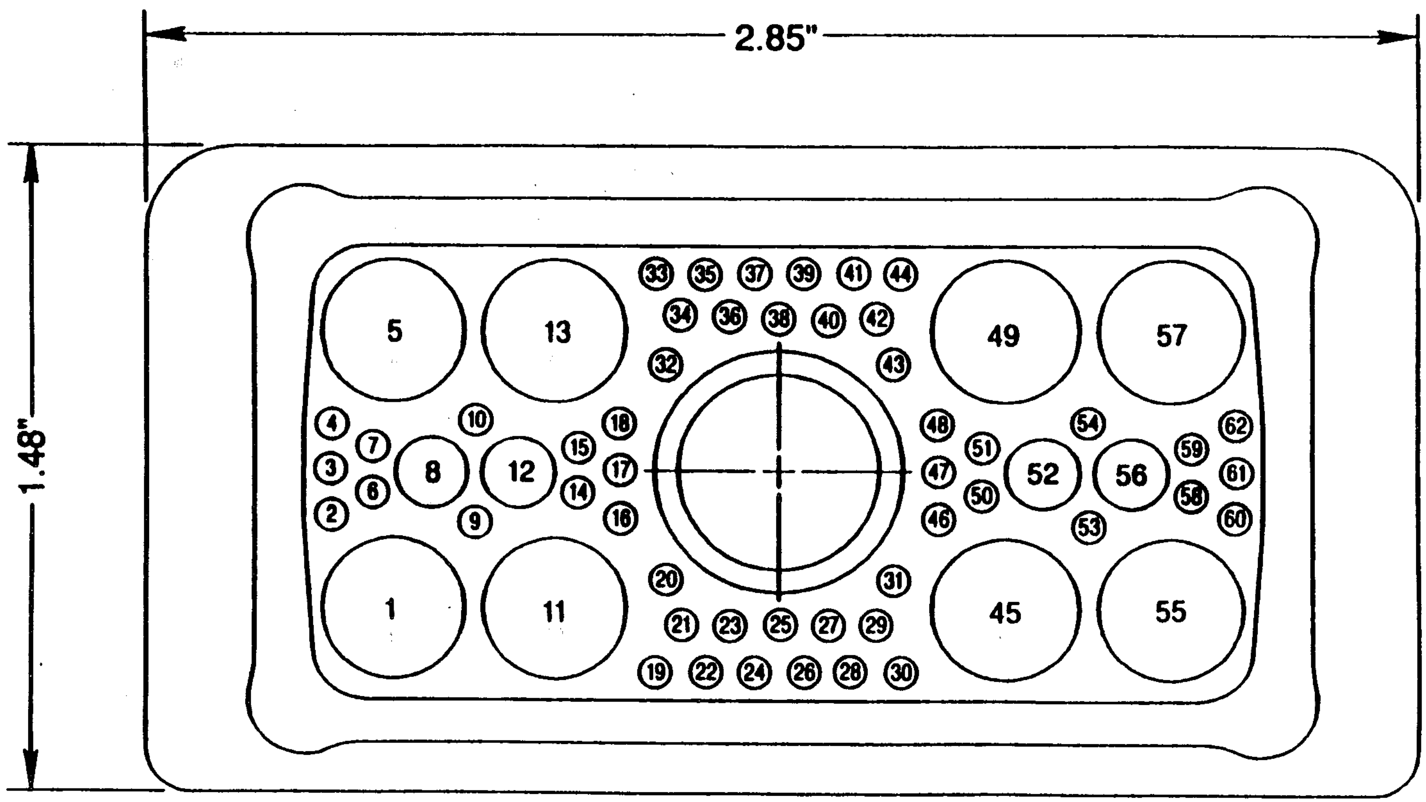

Table 4-11
QDC Wiring List and Pin Definition (As of 10 March 1992)

Function/Qty	Max Signal Spec	Wire Type	Pin Assignment	Pin Count
Anode (1x2)	13.5kV, 1mA, DC	0.06 FEP	1,57	2 Pee Wee HV
K (1x2)	50V, 2mA, 70 MHz	Cheminex 9530H1014 RG180	12,52	2#16 Coaxial
G1 (1x2)	100V, 0.3mA, DC	RG178	8,56	2#16 Coaxial
G2 (1x2)	1.5kV, 0.3mA, DC	0.05 FEP	13,45	2JrHV
G3 (1x2)	0.9kV, 0.5mA, DC	0.05 FEP	11,49	2JrHV
Focus (1x2)	2.8kV, 1mA, DC ***	0.06 FEP	5,55	2JrHV
X deflection (2x2)	lowV, 5.5A p/p 70kHz	#22TP	17,18,47,48	4#22LV
Y deflection (2x2)	lowV, 5.5A p/p 70kHz	#22TP	33,34,42,44	4#22LV
Heater (2x2)	12V, 1.2A, DC	#26	14,15,50,51	4#22LV
Shield Ground (1x2)	lowV, lowA, DC	#26	16,46	2#22LV
CrowBar Trigger (2)	24V, 100mA, DC	#26	37,38	2#22LV
X,Y,Z U Coil (4)	10mV, 1mA, 20kHz	#26 Quad	22,24,26,28	4#22LV
Shield (1)	lowV, lowA, DC	#26	25	1#22LV
Test Lead (1)	lowV, lowA, DC	#26	35	1#22LV
ID Resistor (2)	10V, 10mA, DC	#26	39,40,41	2#22LV
DC Supply (3)	15V, DC	#26	20,31	3#22LV
PROM Leads (6)	lowV, lowA, 100kHz	#26	19,21,23,27,29,30	6#22LV
CRT PROMS (5x2)	lowV, lowA, 100kHz	#26	2,3,4,6,7,58-62	10#22LV
Auxiliary Shield (1)	lowV, lowA, DC	#26	36	1#22LV
NVG Power (2)	12V, 1A, DC	#26	9,10	2#22LV
NVG eject (2)		#26	53,54	3#22LV
Spare (2)		#26	32,43	2#22LV
				8 High Voltage 4 Coaxial [illegible]

***When dynamic focus is used, +/-50V modulation rides on the DC bias.F[illegible] = 400[illegible]

FIGURE 4-21
SIMPLIFIED BLOCK DIAGRAM OF A TYPICAL VCS SYSTEM

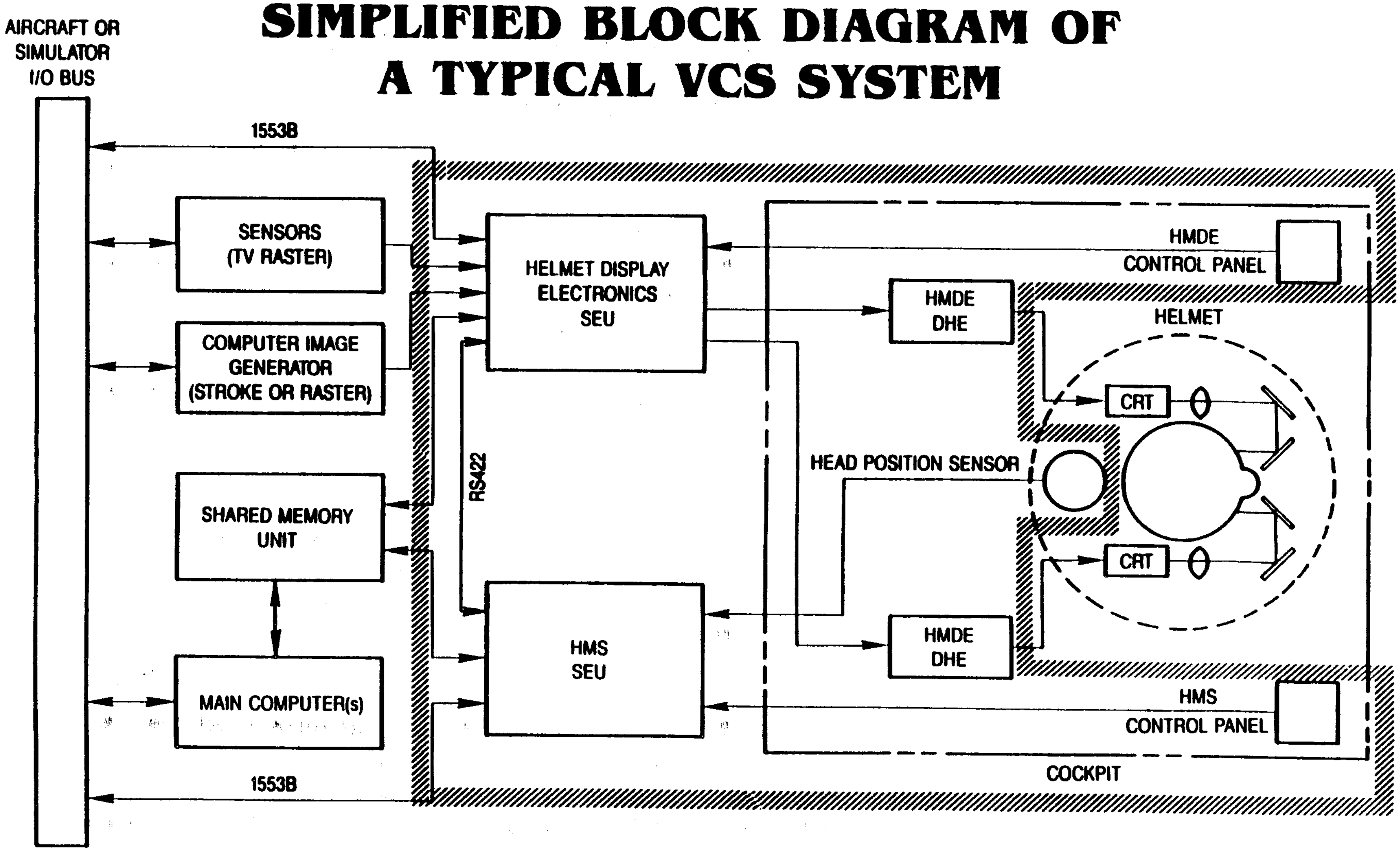

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FIGURE 4-22
REPRESENTATIVE DISPLAY ELECTRONICS BLOCK DIAGRAM

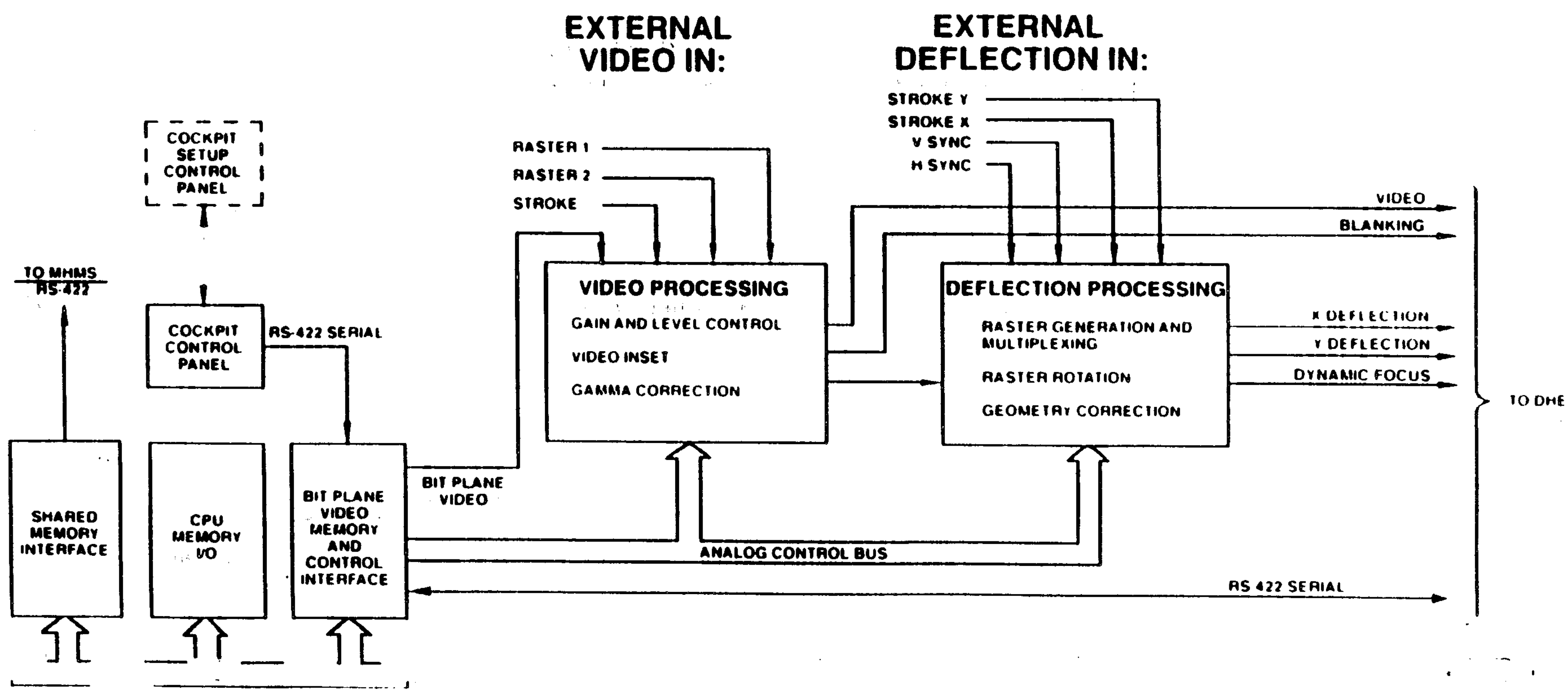

TABLE 4-12
BASIC AHMDE PERFORMANCE

Item	Parameter	Performance
1	Video line rates	Any line rate to 65 kHz scan rate
2	On-axis linearity	At least 0.25%
3	Spot motion and jitter	<0.0005"
4	Step response Small signal (10% display width)	<800 nsec to 0.1% of final position [Rise time = 816 nsec, Fall time = 970 nsec to 0.1%]
	Large signal (100% display width	<2.5 μsec to 0.1% of final position [Rise time = 2.3 μsec, Fall time = 2.39 μsec to 0.1% at 4.6 amps peak-to-peak]
5	Z-axis bandwidth	60 MHz (−3dB) [62 MHz (−3dB)]
6	CRT grid voltage stability	
	Anode	
	Ripple	Better than 0.05%
	Regulation	Better than 0.2%
	Other control voltages (G2, etc.)	
	Ripple	Better than 0.05%
	Regulation	Better than 0.1%
7	Distortion compensation	To 3rd order with cross-product terms
8	Delay lines	10–630 nsec @ 10 nsec steps

[ ] Indicates actual measured system performance

TABLE 4-13
VPD AHMDE CRT POWER SUPPLY CHARACTERISTICS

PARAMETER	VOLTAGE VOLTS		CURRENT MICROAMPS		RIPPLE AND NOISE	REGULATION
	MIN	MAX	MIN	MAX		
ANODE (SCREEN)	10,000	13,500	0.0	300	≤0.05%	≤0.5%
G_4 (FOCUS)	1,000	2,800	0.0	1,000	≤0.05%	≤0.1%
G_3 (DECELERATOR)	300	900	0.0	100	≤0.05%	≤0.1%
G_2 (ACCELERATOR)	500	1,500	0.0	100	≤0.05%	≤0.1%

SECTION 5

HELMET POSITION and ORIENTATION TRACKING SYSTEMS

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This section discusses the functionality and system alternatives that might be considered for the selection and use of a helmet-mounted tracker (HMT) as part of a complete visually-coupled system (VCS).

INTRODUCTION

Many critical pilot activities involve, to some degree, the rapid acquisition of information, the accurate and fast positioning of display symbology depicting system state, and, after suitable cognition time on the pilot's part, the execution of one or more aircraft system state changes. If the man-machine interface (MMI) through which this interaction is being effected is a VCS, then the spatial relationships and positional accuracies of information portrayed on the HMD, as determined by the HMT's position and orientation (P&O) tracking data, are very important. Not only must the quality of HMT attitude and position information be guaranteed to some known and repeatable baseline level of accuracy, but it is also desirable to be able to enhance the VCS's immunity to environmental disturbances to which the HMT or human operator are susceptible (at least in a 'signal-to-noise-sense' to a threshold near or slightly beyond the limits of system-aided human perception).

Quite a few different types of helmet position and orientation tracker (P&OT) systems, from which a HMT function could be implemented, have come and gone over the last 25 years. Some represented real improvements in the technology and many were simply offerings giving a company its own competing system from which maximum profit might be extracted if it was to be incorporated as part of some military production system. The most significant systems have utilized some form of remote sensing system transducer pair based upon optical light sensing concepts or alternating (AC) or static (DC) magnetic fields. Each of these systems may incorporate features that make it the best choice for some use or range of applications. Before comparing the performance of the most important systems (in this author's estimation anyway), it is almost a necessity to examine those features that are important to the functionality and performance of today's HMT systems.

Figure 5.1 depicts a representative HMT configuration when used as part of a VCS. It is worth mentioning that the terminology HMT and helmet-mounted display HMD have often been confused. For the human operator to perform the helmet sighting function properly, one always needs to have a display accessible to the eye for aiming the line-of-sight (LOS) of the transducer. However, this display doesn't have to be a full-functioned HMD. When the HMT is used by itself, the display might be a simple static display driven by an light emitting diode (LED) or incandescent light source, as long as its LOS with respect to the helmet transducer is known or can be established through some form of boresight harmonization routine. The combination of helmet-mounted tracker and sighting reticle functions achieves what is commonly referred to as a helmet-mounted sight (HMS). For good pointing accuracy with negligible parallax errors between the apparent LOS of the HMT display and HMT helmet transducer, the display should be collimated. Multiple LOS reticles may also be implemented to control specified functions or angular corridors as part of the VCS interface.

An HMT coupled with an HMD to form a VCS is often used to drive a gimbaled sensor whose information is displayed on the HMD. If the accuracy of the HMT is better than one half the field-of-view (FOV) of the sensor, then, because of the closed loop system formed through the human

operator, one can think of an almost-zero-error system. This is because, even if there is error between the HMT and the operator's desired pointing angle for the sensor, the operator is free to null out this error by changing his head orientation, and thus the LOS angles from the HMT, and observing the change of the sensor's information position on the HMD.

IMPORTANT FUNCTIONS and PERFORMANCE CRITERIA

Today, HMT P&OT systems are often the odd-man-out when the design of VCS systems is being considered, because respective systems and technologies are considered to be mature. Following such logic, one merely has to pick something off-the-shelf that comes close to meeting often loose specifications on static accuracy, update rate, etc. However, performing a good system integration job for a complete VCS requires a deeper look. Where do you start? Well, there is really no set order to a general discussion of these criteria. As shown in Table 5-1, one has been picked here for this course, but others would probably be just as good.

LOS, ORIENTATION, POSITION, or ALL-of-the-ABOVE

Many early systems, and some systems still in use today, provided only helmet (or head) azimuth (Az) and elevation (El) (LOS) information. This is often sufficient for a given application. However, many of today's more sophisticated applications that display HMT-driven information on the HMD with respect to several coordinate frames, as shown in Figure 5-2, need helmet roll and position information as well. Roll information allows information on the HMD, whose frame of reference is the aircraft, to be derotated using the proper coordinate transformation, allowing the display to stay referenced to the aircraft structure. The addition of X,Y,Z position information allows computer-generated-information (CGI) on the HMD to properly show the parallax with respect to other cockpit structures.

A system offering six-degree-of-freedom (6DOF) (Az, El, roll, X, Y, Z) information also offers other system advantages. For example, portions of an oculometer (eye LOS) function can be implemented just using the HMT. This feature is generally referred to as coordinate intersection cueing (CIC). As shown in Figure 5-3, CIC requires some measurement system with a separate coordinate frame that can be referenced to the coordinate of the HMT's cockpit-mounted transducer. The measurement system can then be used to measure the LOS angles to cockpit locations or switches in its reference frame that can be stored in the HMT memory. During actual operation of the HMT, these stored reference points are converted to the coordinate frame of the cockpit transducer. Then, using the 6DOF information from the observer's LOS, the additional coordinate transformation information is available for eye/reticle-directed switching to cockpit surfaces or switches, as implemented by overlaying the HMT LOS reticule on that cockpit location regardless of head location. Obviously, some sort of feedback most be given to the operator to inform him of the operation.

SYSTEM HEAD COVERAGE and MOTION BOX

Closely associated with P&OT options are the limits of coverage for each parameter and the absolute range over which the helmet can be moved and permit P&OT information to be accurately and reliably resolved.

Most of today's serious applications require that angular coverage follow the head to the normal limits of its angular movements. This means at least ± 180 degrees in azimuth, ± 90 degrees in elevation, and ± 45 degrees in roll. Total 4PI steradian coverage is even more desirable. At this juncture, it is worth noting that the preferred gimbal order for HMT systems is azimuth, elevation, and roll. This corresponds to many sensor system gimbal orders that the HMT might be driving. (Remember, using an azimuth rotation and then an elevation rotation does not usually get one to the same LOS obtained when these rotations are done in reverse order.)

Position coverage is usually specified with respect to some design eye point over a range that is suitable for the range of operator movement allowed. Representative specifications for a

fighter aircraft cockpit might be +20 and - 6 inches in X, ± 12 inches in Y, and ± 6 inches in Z. In reality, especially for situations where the HMT information is driving the information displayed on the HMD, the system ought to provide coverage wherever the pilot can put his head and permit the operator to be able to extract reliable information from the HMD. This type of performance prevents the 'out-of-motion-box' problems that cause data to 'freeze' on the HMD until the head returns to a position where a good LOS solution can be obtained. It also eliminates a perceived flakiness by the user, who may be relying on such a system in life or death situations. A system providing a transducer scheme and associated P&OT tracking algoritHMT that can provide such capability is a real plus.

STATIC ACCURACY

Following close on the heels of any discussion of the above parameters is static accuracy. The true meaning of static accuracy and its importance is very often influenced by the demands of a given system application, the pilot's or operator's state (whether external disturbances, such as vibration or buffeting are a factor), the true signal-to-noise performance of the system, the angular limits for operation, and the particular function for which the system is being used. Static accuracy usually means the performance provided when the system is set internally to provide information over its full angular and positional limits. It is also most often specified as a set of accuracies that degrade as one moves toward the system's maximum angular and positional limits. The limits most often stated are those that represent performance within a few inches of the 'design eye' and ± 30 to ± 70 degrees in Az and El. The importance of this specification is very much influenced by the intended use or primary use of the HMT and/or HMD systems.

An example would be LOS pointing accuracy for a sensor. The sensor may only require 9 milliradian accuracy if the FOV of the sensor is 20 milliradians. However, driving the operator's visual aiming point or LOS, through the use of HMT-driven HMD information, to an earth referenced navigation way-point or bomb target may require 1 to 2 milliradian accuracy, approaching that claimed for the HUD. Actually HUD alignment, when checked, is often more like 3 to 5 milliradians rather than the 0.5 to 1 milliradian that is claimed. Today's best HMT systems, using suitable P&OT algoritHMT and alignment procedures, can achieve static accuracies of 1 to 2 milliradians, at least throughout the angular range normally subtended by the HUD. However, when the HMT is used 'open-loop' to direct systems observed through such media as cockpit transparencies, offset errors arising from prismatic deviation through the transparency, can cause errors (> 1 degree) that overwhelm the basic static accuracy performance of the HMT.

When someone is given a system error performance, its exact meaning must be known. Does it mean that the manufacturer is guaranteeing that all points over a given angular and positional range will be determined to the stated system accuracy? Or is the manufacturer saying that the system accuracy represents some given root means square (RMS) error for an assumed Gaussian distribution, because the estimation errors, of the sampled physical signal are assumed to be Gaussian and uncorrelated. Usually, the second condition is the case, and the errors are stated in terms of circular error probable (CEP). Table 5-2 gives an example of these relationships for two assumed CEP and static accuracy requirement conditions.

RESOLUTION and REPEATABILITY

These two terms are closely related. They also have a bearing on static accuracy performance. The resolution capability of a system generally determines its maximum static accuracy. However, the signal-to-noise (S/N) performance of the transducing scheme and system electronics used also plays a part. Most systems available today provide 12-bits of resolution (1 part in 4096) for each P&O parameter they measure. For an azimuth specification of ± 180 degrees, this means it has a basic angular resolving capability of 0.088 degrees (~0.75 milliradian). If its S/N performance is better than indicated by its gross resolution performance, it might be able to operate over small angular ranges and still provide 12-bit resolution. An example would be ± 90 degrees azimuth determined to 12-bits of resolution, thus providing an angular resolving capability of 0.044 degrees or 2.6 arc minutes. However, because these are

sampled systems, and usually update rate is also important (settling times for the electronics will determine the resolved level of the signal) and cost is also a factor, the angular resolution at the HMT system's angular limits normally reflects the system's performance limits.

Resolution performance of the head tracker can be a significant parameter for head-driven display presentations where small head movements can be detected on the HMD presentation under conditions of high apparent magnification. Twelve-bit P&O tracking systems have been observed to cause undesirable and detectable discrete jumps in the location of the display imagery on the HMD during small head movements. Fourteen-bit systems seem to provide enough additional resolution to make this artifact virtually undetectable. Some systems providing resolution to 14-bits do exist. For full angular coverage, such a system can provide an angular resolution of almost 0.02 degrees. HMT systems providing higher resolution are often to be preferred for binocular HMD applications involving high raster line rates and partial overlap of the monocular fields, since they offer the potential of better symbology placement for objects viewed by both eyes in the HMD's overlap region.

There are tradeoffs associated with the improved performance. Achieving the added signal/noise ratio (SNR) needed to attain an honest 14-bit system often impacts the transducer and electronics design. For example, the AC Magnetic HMT (MHMT) requires a larger source. The larger sources measure 1.25 inches to 1.5 inches square as compared to the normal one inch square source and weigh between 7.5 and 9 ounces, an increase of several ounces. The ideal mounting location in fighter aircraft is on the cockpit canopy behind the pilot. The larger and heavier MHMT source may be too heavy for mounting in some cockpit canopies (e.g., the F-16) because birdstrike-induced canopy waves are more prone to cause canopy failure with the heavier MHMT source mounted on the canopy.

The other troublesome area involving system resolution or accuracy performance is its performance when the range for full resolution performance is reached. Does the system just quit operating, or does its performance degrade gracefully. For example, a 14-bit system might perform at full resolution out to a distance of 40 inches between the cockpit and helmet transducers, then degrade gracefully to 13-bits between 40 and 46 inches, to 12-bits between 46 and 50 inches, etc., for conditions where the maximum full resolution source-sensor range is exceeded.

Repeatability is closely related to resolution and to how well the complete system approaches the performance of an idealized linear system. It is important, because it indicates the variation in measurement one might expect by making repeated measurements at the same position and orientation sample point. Thus, it can indicate the relative stability of the location of HMT-driven information on the HMD. Generally, repeatability is specified at two or three times the system resolution limit for any value determined within normal operating limits, regardless of the absolute accuracy of that value. Repeatability worse than three times the resolution limit can be an indication of flaws in the design of the system.

UPDATE RATE and THROUGHPUT RATE

This particular performance measure for HMT systems has been a point of contention and misunderstanding on an almost consistent basis. Often, the argument will be advanced that, based upon the application requirements, a certain update rate is sufficient. In the past, this argument has sometimes been sufficient. However, today's advanced applications, especially if they involve HMT-driven computer-generated information (CGI) on the HMD, demand as high an update rate as most systems can provide. Indeed, even if the computer graphics update rate is relatively slow, several samples of a high update rate HMT can be used for predicting the next update point for the CGI display on the HMD, thus improving the apparent data throughput rate for the entire system. To be meaningful, update rate must be explained in terms of the sampling process and P&OT algorithm used. For instance, is one update used solely for sampling the sensed signal to remove unwanted disturbances from the signal by means of various digital

filtering schemes? Or, is the algorithm recursive in nature, requiring two or more updates to approach some nominal steady-state error?

As usually defined, update rate is the rate at which the signal is sampled and at which P&OT data appears at the output. Throughput rate is the time or number of samples required for an input to be reflected as an output from the HMT system. Throughput rate is a better reflection of the bandwidth of the system and its dynamic error. However, even throughput rate must be considered in terms of how many updates are required for a step input to show up on the system's output to an accuracy level that represents its claimed static accuracy or steady state error.

Most HMT system P&O algoritHMT require at least two update cycles to obtain good convergence to the actual dynamic head P&O inputs. This is particularly true for the MHMT systems. Figure 5-4 indicates the error performance obtained for a new type of minimum-variance linear estimation algorithm. This algorithm provides a system error that is minimum in a least-squared-error sense. It is also designed to track field conditions at the helmet sensor, and in laboratory tests, at least, has demonstrated the capability to track the sensor down to conductive surfaces. The system hardware that was designed to run this algorithm operates at a 240-updates-per-second (UPS) rate. For this type of algorithm, the higher update rate reduces the algorithm convergence problem down to manageable levels for the human operator head rates (0-250 degrees/second) most often encountered.

What then, besides improving the performance of superior forms of P&OT algoritHMT, are some good reasons for requiring an improved update for the HMT? One already mentioned is that it also aids the throughput delay problems for computer-generated imagery systems which must place their imagery on the HMD according to the MHMT P&O updates. Using multiple HMT updates provided at high rates for a system update rate that may be much lower can permit elegant prediction algoritHMT to be utilized thereby improving the effective bandwidth of system functions.

Another is that a higher update rate aids one area of MHMT performance that is particularly hard to quantify: system dynamic accuracy. The problem with this requirement is its measurement. Past development efforts that have investigated this problem have resulted in budgetary estimates of three to four hundred thousand dollars to produce an adequate test fixture. This is an amount that meager development budgets have not been able to handle with competing commitments of greater overall import. Perhaps a good alternative for the HMT is achieving higher update rates which reduce the latency between the measured and real head position and orientation and, thus, inherently improve system dynamic accuracy.

Finally, the evolution of VCS interfaces in the military aircraft cockpit and elsewhere is leading towards an overall integration of human sensory interfaces to maximize the use of the human's perceptual and cognitive functions. Foremost among the new integrated capabilities coming on line for the man-machine-interface is auditory localization. The human's visual system has relatively high resolution, but is moderately slow. The human's auditory system is relatively coarse but much faster. Researchers working on the auditory localization problem indicate that people can move their heads between 200 and 500 degrees per second without blur and that, at the most sensitive locations, human localization error is about one degree. Maximum head rates over small arcs fall in the range of 800 to 1000 degrees per second. Some HMT algoritHMT require at least one update for waveform sampling and then another to produce an output to better than one degree error and may have convergence problems if sensor orientation changes by more and one or two degrees per update. These operating characteristics beg the question of the effect on latency for the auditory localization system, which may by as important as rate. Since no systems providing these rates have been built, the effect on 3-D audio displays is not well defined. This discussion implies that sampling rates between 500 and perhaps 1600 updates per second may ultimately be desired, depending upon the system type, its algorithm, and throughput qualities.

SYSTEM INTERFACES

Today's HMT, when used as part of a modern VCS, needs to accommodate a number of system interfaces. Systems geared for military cockpit use normally provide a 1553B interface. The update rate of 50 UPS on the 1553B bus is sufficient for some uses, but too slow for others, such as image derotation on the HMD. This function may have to operate at rates of 60 to 120 UPS or higher to maintain synchronization with the helmet-display raster or calligraphic imagery. A special interface, often a dedicated RS-422 channel, is required. Other interfaces, such as ethernet or a shared-memory interface, may be required, especially for simulator applications. The system must also be capable of being 'synced' to an external clock that is controlling the computer-generated information or the refresh control for the HMD display. This requirement is often critical for CGI moving objects, whose placement on the HMD is driven by the HMT outputs. To prevent observable jitter in the CGI-based object movements, the HMT may be required to update itself at some integer multiple of the system's update rate. Finally, other types of user-defined interfaces may sometimes be required for special applications.

OTHER SYSTEM ISSUES

There are a number of other systems issues that ought to be considered in selecting an HMT system. Often these are not directly related to performance, but may ultimately affect system performance because of limitations imposed by the operating environment that limit system performance.

One important issue is the number of transducers that must be installed and aligned to achieve full system head P&OT coverage. A system requiring just one transducer to achieve full coverage is a decided advantage. It takes up less space, especially in cramped fighter cockpits. It can be aligned to the vehicle datum line. Relative alignment to other cockpit transducers that a system with multiple transducer requires is not an issue. Nor is crossover from one transducer's coverage limits to another's that may produce offset errors. Although, this problem can be minimized if coverage overlaps and the relative offsets are interpolated to eliminate any abrupt change in P&O values.

Another issue, from which a whole series of questions arises, relates to the type of transducer alignment hardware provided. Is it expensive and labor intensive? Or relatively cheap and automated in its use? Must multiple transducers be aligned, and how is relative alignment checked? Does the alignment fixture allow one to test system P&OT static accuracy at the same time, or must a different fixture be procured for this function? Can the customer become proficient enough to align the system himself, or must he continually return to the maker of the system for such help?

Finally, important issues relating to system integration and long-term performance must be addressed. This area can generate another set of questions whose relative importance must always be balanced against the specific application requirements. One very important issue is the system susceptibility to performance degradation due to external disturbances and materials that will be encountered in its operating environment. Can these factors be compensated for, and how easily? Systems that transduce magnetic energy are bothered by conductive and ferromagnetic materials and stray fields from the helmet-mounted CRTs. Systems that transduce light energy may be bothered by sunlight or laser weapons. Is the helmet-mounted transducer hardware compact, leaving more room for other system attachments and relatively immune to helmet flexure or obscuration by human motion? Or, does the system require a significant area of real estate on the helmet surface, making it susceptible to helmet flexure or obscuration of its transduced energy by human motion. Is it rugged and relatively immune to the abuse that personal equipment receives during normal use?

PERFORMANCE SPECIFICATIONS for SEVERAL HMT SYSTEM TYPES

The discussion just concluded has attempted to cover some of the most important issues surrounding the selection and use of HMT equipment as part of a VCS. It is not possible, within the forum of this course, to be totally inclusive, especially with the application-dependence of particular requirements and technology that is constantly evolving. Tables 5-3, 5-4, and 5-5 provide a summary of basic performance characteristics for some of the newer systems. These tables primarily chart the trend in performance and can hardly be used to make a system acquisition decision. This requires a thorough understanding of one's application and close coordination with each system vendor.

The FUTURE

It might have been obvious from some parts of this section's discussion, as to the expected evolutionary trend of the technology. It will, of course, depend upon which functions the HMT is required to drive as part of the MMI. Certainly one can expect higher update rates, 14-bit resolution will probably become the standard over the 12-bit systems that currently dominate, and system accuracy, and alignment problems will undergo at least moderate improvement.

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FIGURE 5-1
VISUALLY COUPLED SYSTEM

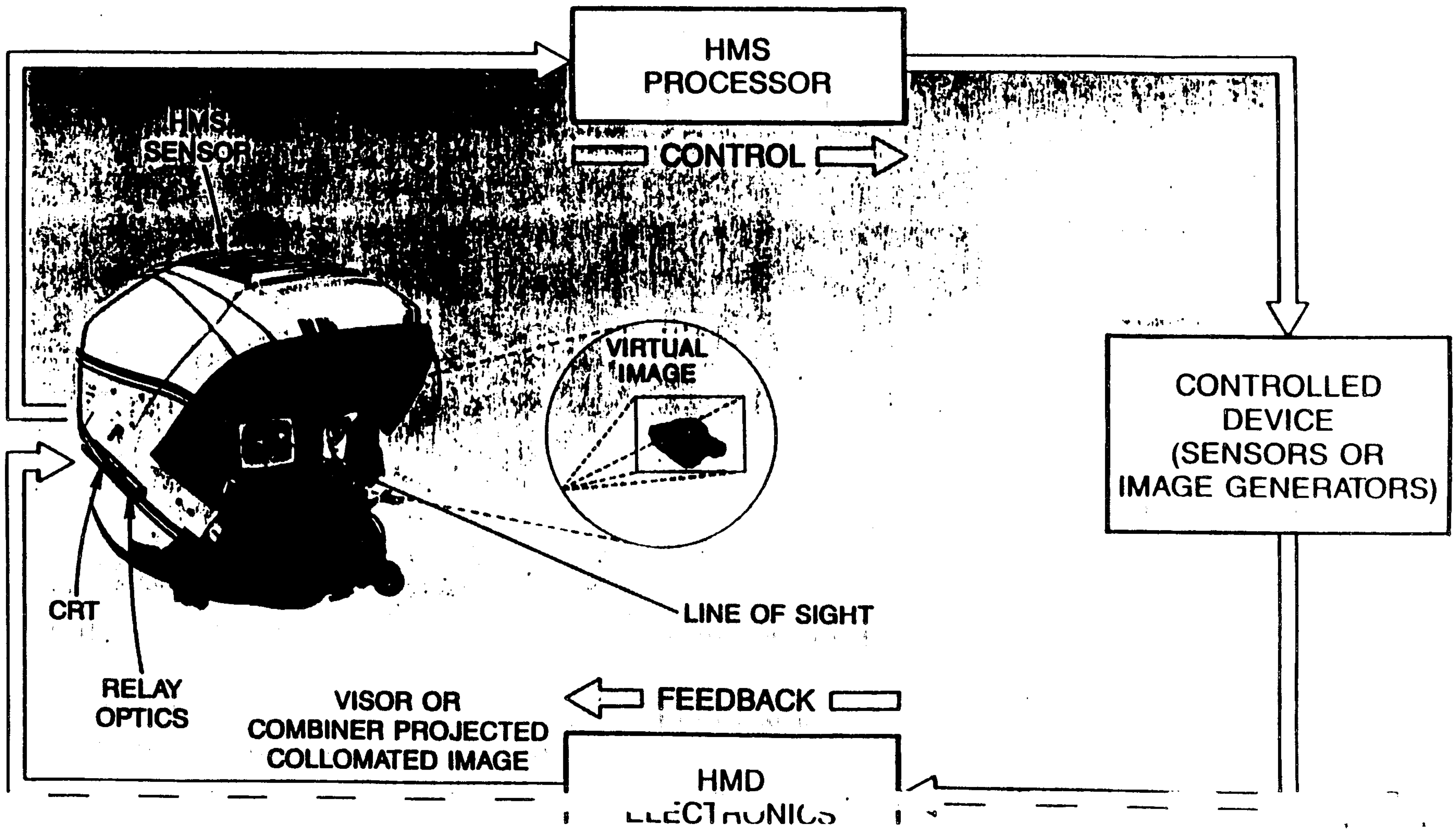

TABLE 5-1
Helmet Tracking System Features and Performance

Parameter	Performance
Line-of-Sight, Orientation, Position, or All-of-the-Above	Az, El, Roll, X, Y, Z ---------------- ?
System Head Coverage and Motion Box	Limited or Full Coverage ------- ?
Static Accuracy (How much is enough and where?)	1 milliradian or Several --------- ?
Resolution and Repeatability	16, 14, or 12-Bits ------------------ ?
Uprate Rate and Throughput Rate	800 Updates/Second or More --- ?
System Interfaces	1553B, RS-422, Etc. --------------- ?
Other System Issues	BIS and More ------------------------- ?

FIGURE 5-2
VCS REFERENCE FRAMES

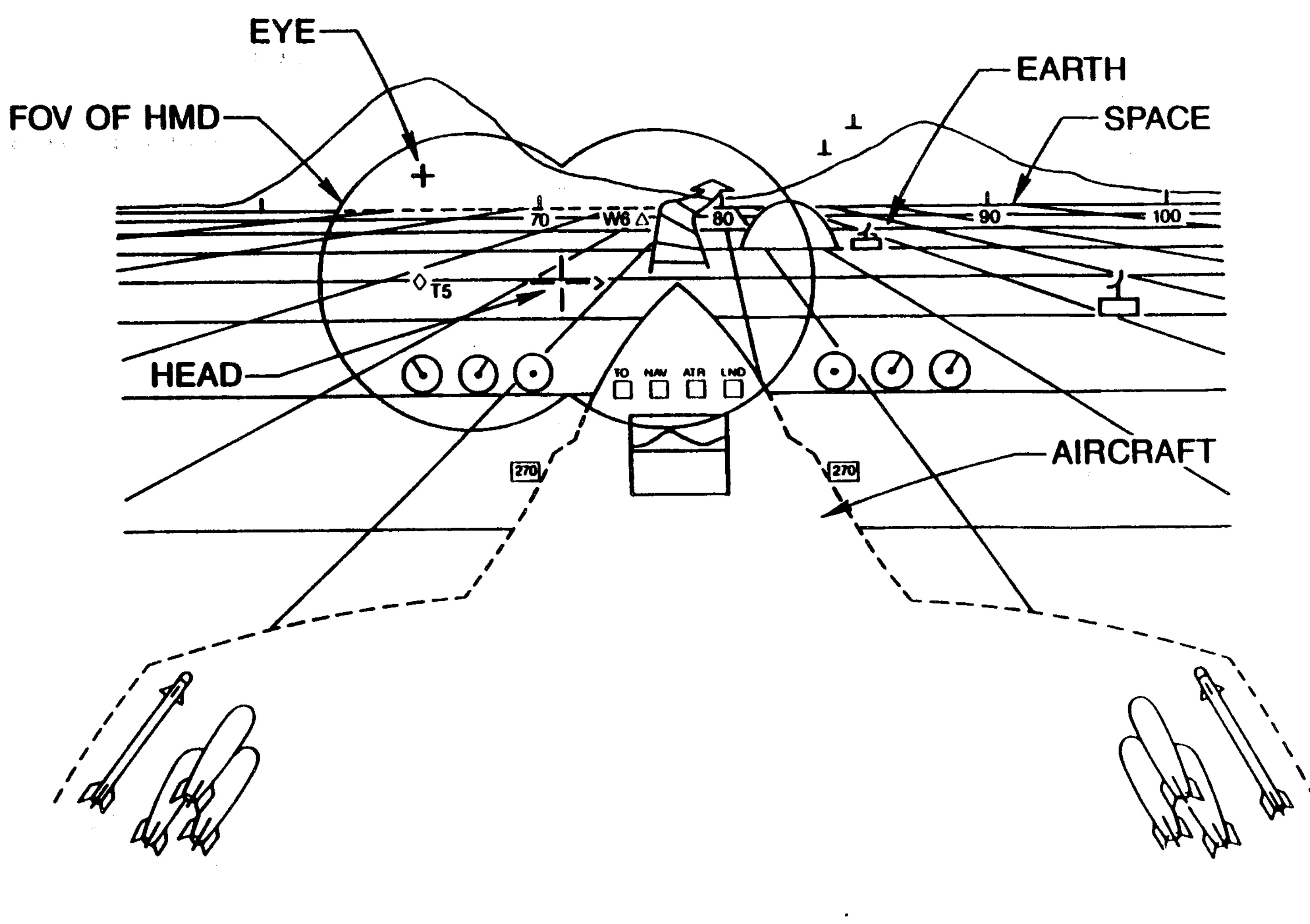

FIGURE 5-3
COORDINATE INTERSECTION
CUEING GEOMETRY

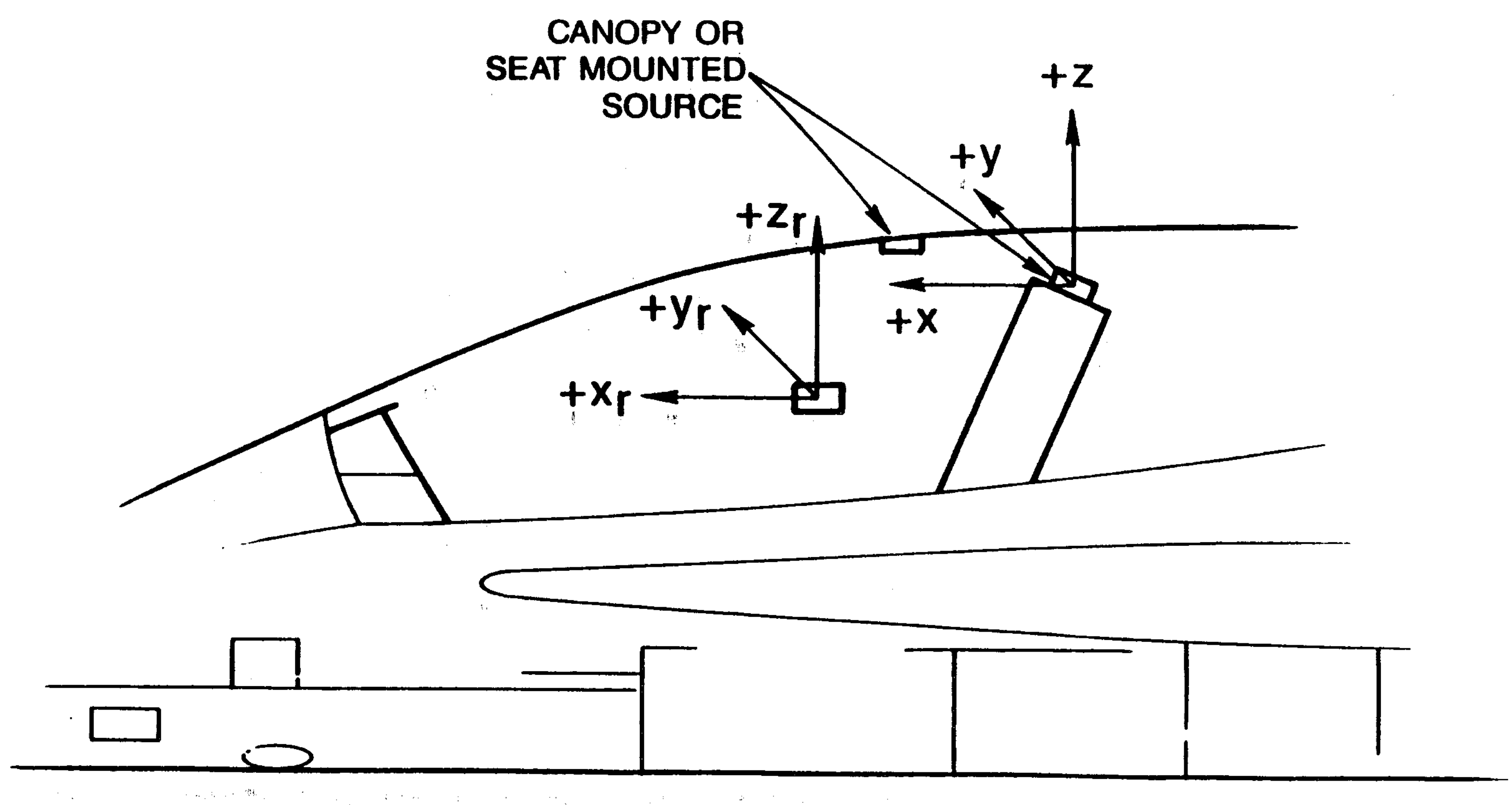

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TABLE 5-2
MHMS SYSTEM PERFORMANCE / ERROR CRITERIA

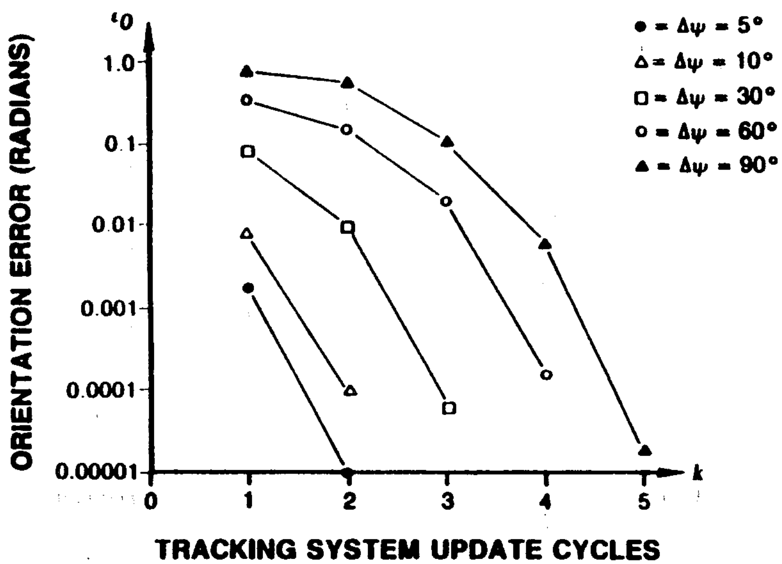
RELATIONSHIP OF CEP AND RMS ERRORS

CEP	STATIC ACCURACY REQUIREMENT	R (FROM (6))	σ(RMS) DEGREES	σ(RMS) RADIANS
0.50	0.2°	$1.18\sigma = 0.2°$	0.169°	0.00295
0.99	0.4°	$3.03\sigma = 0.4°$	0.132°	0.00230

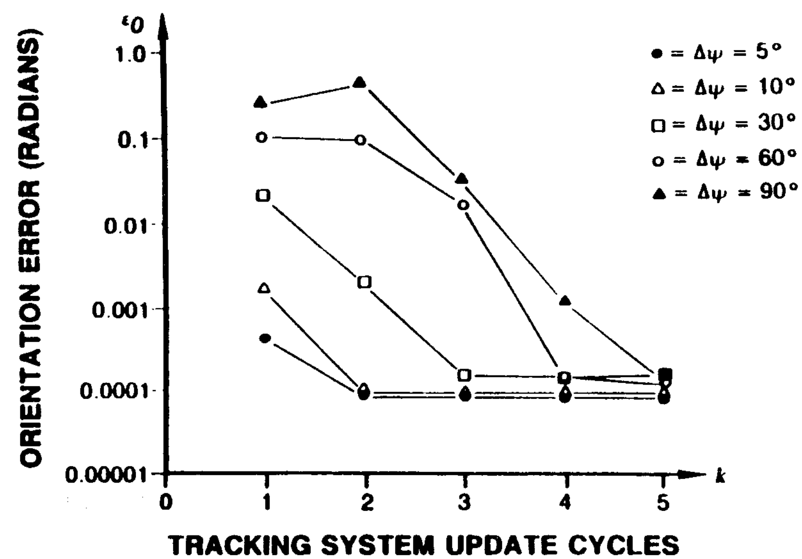
$$R^2 = -2\sigma^2 \ln[\,1 - P(r \leq R)\,]$$

Where: $P(r \leq R) = 1 - \exp(-R / 2\sigma^2)$ is the probability of a radial error not exceeding a radius of R.

FIGURE 5-4
REPRESENTATIVE MVLE ORIENTATION TRACKING PERFORMANCE FOR FREE-SPACE AND FIXED SCATTERING ENVIRONMENTS



FREE SPACE FOR
ERROR PERFORMANCE



ERROR PERFORMANCE IN THE
PRESENCE OF 2 FIXED SCATTERERS

TABLE 5-3
REPRESENTATIVE AC MAGNETIC HMT PERFORMANCE

Item	Parameter	Performance
1	Angular coverage Azimuth Elevation Roll	 ±180° ± 90° ±180°
2	Normal cockpit motion box coverage (can be essentially the physical limits of the cockpit)* X direction Y direction Z direction *Can provide essentially unlimited coverage if sensor and miniature CRTs are mounted so that obscuration of the signal by the CRT cannot occur	 ±20" ±15" ± 8"
3	Static angular accuracy [line-of-sight (LOS) error for reduced area coverage of ±70° in azimuth/elevation and ±30° roll] 50% circular error (CE) 99% CE	 <0.2° (1-3 milliradians) <0.4° (6-7 milliradians)
4	Static angular accuarcy (for conditions stated in 1 above) 50% CE 99% CE	 <0.3° (3-5 milliradians) <0.5° (7-9 milliradians)
5	Static translational accuracy X, Y, and Z	 ≤0.1" plus 1% of separation distance between source and sensor
6	Resolution Angular Translational	 ~0.022° Better than 0.025"
7	Repeatability	Twice resolution limits in (6)
8	Update rate(s) a) MHMS with basic tracking algorithms b) Two-cockpit operation	 240 updates/sec (U/S) 120 (U/S)
9	Transducer size	1.25" squared

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TABLE 5-4
REPRESENTATIVE DC MAGNETIC HMT PERFORMANCE

Item	Parameter	Performance
1	Angular coverage Azimuth Elevation Roll	 ±180° ± 90° ±180°
2	Normal cockpit motion box coverage (can be essentially the physical limits of the cockpit) X direction Y direction Z direction	 ±3′ ±3′ ±3′
3	Static angular accuracy [line-of-sight (LOS) error for reduced area coverage of ±70° in azimuth/elevation and ±30° roll] 50% circular error (CE) 99% CE	 <0.5° (8-10 milliradians)
4	Static angular accuarcy (for conditions stated in 1 above) 50% CE 99% CE	 <0.3° (4-5 milliradians) <0.5° (8-9 milliradians)
5	Static translational accuracy X, Y, and Z	 ≤0.1″ plus 1% of separation distance between source and sensor
6	Resolution Angular Translational	 ~0.08° Better than 0.03″
7	Repeatability	Twice resolution limits in (6)
8	Update rate(s) a) MHMS with basic tracking algorithms b) Two-cockpit operation	 100 updates/sec (U/S) 100 (U/S)
9	Transducer size	3″ squared

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TABLE 5-5
REPRESENTATIVE OPTICAL HMT PERFORMANCE

Item	Parameter	Performance
1	Angular coverage Azimuth Elevation Roll May require two cockpit receivers	 ±180° ± 90° ±180°
2	Normal cockpit motion box coverage (can be essentially the physical limits of the cockpit) X, Y, Z total	 ±18" radius
3	Static angular accuracy [line-of-sight (LOS) error for reduced area coverage of ±70° in azimuth/elevation and ±30° roll] 95% circular error (CE)	 ~0.1° (1-2 milliradians)
4	Static angular accuarcy (for conditions stated in 1 above) 98% CE No cockpit mapping required	 ~0.2° (2-3 milliradians)
5	Static translational accuracy X, Y, and Z	 ≤0.1"
6	Resolution Angular Translational	 ~0.017° Better than 0.01"
7	Repeatability	Twice resolution limits in (6)
8	Update rate(s) a) HMS with basic tracking algorithms b) Two-cockpit operation	 240 updates/sec (U/S) 120 (U/S)
9	Transducer size	?

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SECTION 6

INTEGRATION ISSUES: HELMET-MOUNTED DISPLAY (HMD) OPTICS AND VISION

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INTRODUCTION

The previous section have provided considerable information on the major components of visually-coupled system (VCS); the purpose of this and the next section is to address issues associated with integrating these components together with the operator.

ADJUSTMENTS

In order for the HMD to be usable at all, it is critical that it be adjusted properly to each user. Since individuals vary widely in their head sizes and eye positions relative to the head, it is necessary to provide means to mechanically adjust the optical system to get it correctly aligned to the two eyes (assuming a binocular HMD). These adjustments may include vertical, tilt, and fore/aft. If the device is binocular, then it is also necessary to provide means of adjusting the distance between the two exit pupils. This distance is referred to as the inter-pupillary distance (IPD). The eyes are not always centered precisely on either side of the nose, so, if the HMD produces a fairly small exit pupil, it may be necessary to provide individual right and left side lateral adjustment. Most binoculars are designed to be adjusted from 54 to 72 mm IPD, although a larger range (50mm to 73mm) has been recommended by Self (1986). One must carefully consider the user population to ensure that the mechanical adjustment ranges are appropriate.

Another key adjustment variable is image distance or eyepiece focus setting. It is much easier to produce an HMD that has a fixed image distance, but this means the user population must be able to focus at that distance. If the HMD is built so as to permit the use of eyeglasses, then this should not be a problem. However, if the HMD is not compatible with eyeglasses use then the HMD should have a means of focus adjustment (this will only correct for near-sightedness or far-sightedness; it will not be able to correct for astigmatism). With older individuals who can no longer change their accommodation, the HMD must not have too much field curvature, else when part of the FOV is in focus the rest will be out of focus since eye refocusing is not possible.

ENVIRONMENT

The environment in which the HMD will be used will impact its design. For example, if the HMD is to be used in a brightly lit environment (daylight), then the HMD combiner must be designed to reduce the external light sufficiently so the HMD image can be seen, but not so much that it produces too large a disparity in luminance between the HMD field-of-view (FOV) and the surrounding area that has no HMD image. If the HMD is to be used in conjunction with other displays/instruments or external scenes, it must be designed to permit unfettered viewing around the HMD (e.g., looking under the night vision goggles (NVGs) at flight instruments).

BINOCULAR EFFECTS

There are several undesirable visual effects that may occur in binocular HMDs. These include binocular disparity (retinal rivalry) due to luminance imbalance, image misalignment, accommodation differences, and/or differential distortion. When binocular disparity is sufficiently severe. the observer may see double images or may suppress one of the two disparate images. A more insidious problem is when the binocular disparity is not large enough to cause a loss of image fusion, but is enough to result in 'eye strain' or visual fatigue. This can lead to eye strain headache or nausea during extended use, but may not show any effects during short term use. There have been some efforts to define the limits for these types of parameters (Farrell and Booth, 1984; Gold, 1970; Self, 1973 and 1986; Landau, 1990).

Table 6.1 is a summary of some of the recommended values for several binocular disparity parameters. These values are those recommended for long-term wearing comfort and NOT for image fusion threshold. The wide range of recommend values implies that there is still work to be done in this area to better determine appropriate binocular image tolerances.

Table 6-1. Tolerances for alignment of binocular displays.

	Recommended Tolerance Source			
Parameter	ANVIS-6 NVG Mil Spec	Mil Hndbk 141 (1962	Gold (1971)**	Farrell & Booth (1984)**
Vertical (Dipvergence)	+/- 30 min	8 to 17 min	+/- 3.4 min	+/- 10 min
Horizontal				
Convergence	60 min	< 17 min	8.6 min	2.7 DEG
Divergence	60 min	< 17 min	3.4 min	0
Rotation Difference	2 DEG	10 min *	10 min *	29 min *
Magnification Difference	10% ***	2%	0.28% *	0.83% *

* NOTE: The specification for these was stated in terms of the maximum allowed vertical misalignment at the edge of the FOV. Therefore the specification is dependent on FOV. To permit comparisons the values shown are for a 40 degree FOV which is the same as the ANVIS-6 NVG.

** NOTE: These values obtained from Self, 1986.

*** NOTE: The specification states that system magnification shall be +/- 5% but does not specify differences between oculars.
Worst case would be for one ocular to be +5% and the other to be -5% thus the 10% value.

MISCELLANEOUS

There are many other parameters that affect the overall acceptability and performance of an HMD. Two of the key parameters that are usually acknowledged, but that really don't receive the attention they should, are size and weight. For many operational applications, if the HMD is unacceptable from the standpoint of size and/or weight, then it really doesn't matter how wonderful the rest of the performance characteristics are. Additionally, two other aspects that have received relatively little attention are comfort and fit. These are also exceedingly important for both commercial and military acceptance of HMDs (and, unfortunately, also exceedingly difficult to accomplish and measure).

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SECTION 7

INTEGRATION ISSUES: ELECTRONICS/IMAGE SOURCE

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INTRODUCTION

Sections 3, 4, and 5 have discussed the current state of helmet-mounted display (HMD) component technology and some future trends. These sections also provided justifications for the current state of VCS technology and rationales behind new development activities in progress. As such, the preceding discussions have already touched upon issues that have a close association with system design and integration. This section attempts to cover some of the broader themes, issues, and tradeoffs that might be considered for the systems and technology at hand or that could soon be available.

The solution to the successful utilization of visually-coupled system (VCS) technology for computer-driven and/or sensor-enhanced systems includes the solution to a number of interrelated component technology, performance and system integration problems that cross the boundaries of many technical disciplines. A few of these are:

1. Providing further insight into, and perhaps some solutions to, the more important remaining HMD human factors problems. Among them are the establishment of appropriate instantaneous fields-of-view (FOVs) for specific categories of missions or vehicle types (which are defensible with statistically meaningful quantitative data), eye accommodation as it relates to viewing collimated see-through displays, and binocular rivalry issues (either between eyes or between the display and ambient imagery),

2. Providing a display with a visual interface supporting sensor-generated and computer-generated information that reduces operator workload and demonstrates quantifiable improvements in operator performance,

3. Providing a helmet display, image source, and image-source electronics combination that optimizes their own interface, can be easily adjusted for variations in human and hardware parameters, and supports the display of computer-based and sensor-based information, such that the entire sensor/display subsystem is not display limited,

4. Providing a VCS with the necessary spatial and temporal bandwidth, while maintaining modest head-borne weight and an equipment configuration that is compatible with current aircraft ejection seats and safe for rapid ground-egress in explosive vapor environments,

5. Providing, or at least approaching, day-night operability with one HMD system for military aircraft applications,

6. Evolving a helmet-mounted position and orientation tracking system that fully supports its own cockpit integration, its integration with other subsystems comprising the entire VCS, and provides a usable and reliable man-machine interface (MMI),

7. Solving the biodynamic interference suppression problem for the helmet display for environments where vibration is a problem, and perhaps most important of all,

8. Pursuing a vigorous discourse with the purveyors of either the military avionics and weapons or commercial equipment, to educate them to the fact that their systems must be designed to effect maximum advantage from the visually-coupled system interface for such man-machine-interfaces to reach their maximum cost/benefit potential.

The above list, which is not exhaustive, represents a compilation of issues that, in the author's experience, has been observed to be important and needs further work before one can feel reasonably secure about the general adoption of VCS technology. This half-day course cannot hope to cover all of the aforementioned issues in detail. The discussion that follows in this section will attempt to provide information and guidance on system integration issues based upon both experience and recent technology development efforts that may offer solutions not previously available, or provoke new thinking about ways to perfect the technology. The presentation will also not attempt to be comprehensive, but, instead, try to highlight what are believed to be a few of the key issues. The order of presentation will proceed logically from the display optics, its integration with the CRT, the CRT and signal conduit, the display electronics, and finally, the helmet tracking system issues.

HMD SYSTEM INTEGRATION ISSUES

HELMET DISPLAY OPTICS

As indicated in Figure 4-3, besides the size and weight of the HMD optics, **contrast** performance is probably the most important issue for the display optics. Light transmission efficiency is critical for maintaining both display contrast and CRT faceplate contrast and resolution, which degrades quickly for imagery as a CRT's upper luminance ranges are reached. The assumption made for what follows, is that a see-through HMD is the desired system choice. In the modern battlefield with variable wavelength laser threats or the advent of cockpits without windscreen or canopy transparencies, this may not be the case. Greater use of unmanned aerospace vehicles (UAVs) may also change the relative need for see-through HMDs. But pilots, despite their particular environment, may still demand to see through their helmet visor or HMD transparencies, if only to view cockpit displays.

On see-through HMDs, combiner design usually has the biggest effect on the transmission efficiency of light from the HMD image source, as well as from the ambient scene. Three basic types of combiners exist that are seriously considered for use with see-through HMDs. On-axis designs that utilize either conventional beamsplitter-combiner or prism-combiner configurations using half-silvered reflective surfaces, or the equivalent, are the most inefficient. Often less than 20 percent of the light originating from the image source can reach the eye. On-axis designs that utilize either conventional beamsplitter-combiner or prism-combiner configurations using different fold geometry and angle-sensitive coatings can raise the percentage of light reaching the eye from the image source to about 50 percent. Finally, off-axis, optical designs using only a highly reflective combiner design can push the percentage of light reaching the eye from the image source to about 70 percent. All these systems can also benefit from some color contrast enhancement that the use of narrowband image sources and narrowband reflective coatings provide with efficient dichroic coatings. The reflected and the transmitted light of a beamsplitter total very nearly 100 percent and their ratios can be almost any value.

The optimization of a particular design falling into any of the above three categories of HMD optical systems for FOV, exit pupil, weight, and size, often results in severe compromises for the optical design and the types of aberration corrections that can be accommodated. One of the first types of corrections not made in many designs is chromatic aberration correction, because its elimination significantly reduces the number of required optical elements and weight in the relay optics section of the HMD. This is unfortunate, because some of the best phosphors, such as P53, that resist thermal saturation effects when driven to high luminance levels, exhibit emission peaks centered about several spectral

wavelengths. An optical design optimized for one narrow band of wavelengths and lacking chromatic aberration correction can exhibit lateral and/or axial color problems with phosphors like P53. When using of P53 and an HMD optimized for transmitting yellow-green light, as most are, lateral color usually appears as multiple images of red and blue displaced in the HMD's visual space from the primary green image. The visual sensation of chromatic aberrations will vary under certain viewing conditions. The solution most often used is to place a filter somewhere in the optical path to remove the unwanted spectral bands. Unfortunately, 20 percent or more of the light from the desired spectral band is also lost. Also, because of the often low f-numbers of the optics and the angles over which the filters are effective, some CRT/ambient luminance conditions can still result in lateral color being observed on the HMD combiner.

Complicated aspherical designs and gradient index optics designs have been attempted to provide comprehensive aberration correction while minimizing increased weight. These approaches do not appear to provide the answer, when actual hardware performance, or cost, or both, are considered. However, recent advancements in surface-relief diffractive (SRD) optics may provide the solution. The focal length of a lens with no chromatic correction varies inversely with the wavelength of the incident light. Thus, red wavelengths focus closer to the lens than do blue wavelengths, which is just the opposite of an ordinary refractive lens. When used in combination with refractive lens, diffractive lenses can function effectively in broadband optical designs. Refractive/diffractive combinations produce hybrids where both elements have positive optical power that can lead to a significant reduction in the required material and weight of the hybrid lens. Also, because the Abbe v-number of the diffractive element is so low (because the diffractive lens is so dispersive), most of the optical power resides in the refractive element, generally making the diffractive element easier to fabricate and to align, because the surface-relief diffractive lens can also be fabricated as an integral part of the refractive lens element.

There is also a negative side to obtaining broadband performance. It is the wavelength dependence of diffraction efficiency. Since diffractive lenses can be thought of as 'Modulo Pi' lenses, other illumination wavelengths no longer experience constructive interference, with a resultant drop in diffraction efficiency. A reduction in the diffraction efficiency in the principal order implies that there is an increase in the amount of light energy in other diffraction orders, which can contribute to the phenomena associated with broadband defects of diffractive optical systems known as 'veiling glare' in the image plane. This defect tends to produce a reduction in the display's contrast. By careful design, it may be possible to adjust the diffractive power of the system to defocus the extraneous images or vignette them out of the system so that the majority of light energy in other diffraction orders does not lead to a reduction in contrast. Figure 7-1 depicts some representative results with SRD optics technology relating to HMD design. More conclusive results await at least the completion of a project that, basically, is just beginning.

VARIABLE TRANSMISSION HELMET TRANSPARENCIES

As mentioned earlier, laser threats may be a battlefield condition that can no longer be ignored. It may be reasonable to expect that the windscreen and canopy transparencies should provide part or all of the protection from such a threat. Then the system design burden the HMD must bear becomes more reasonable.

An alternative solution to obtaining improved display contrast across the range of ambient lighting conditions that exist in operational flight is to vary the transmission of ambient light based upon external conditions and the known performance limitations of the image source. One alternative considered throughout the history of VCSs is a variable transmittance visor or combiner transparency. In the past, such attempts have met with failure for a number of reasons. Among them were the variable transmission material could not be manufactured to conform to the curved surfaces needed for helmet transparencies or

they required front-back surface separation tolerances that could not be met leading to significant variations in light transmission efficiency over the entire surface. Also, most systems considered used polarizing material. where minimum transmission was less than about 3.5 percent at best.

A somewhat different approach seems to offer significant hope that this problem will be overcome. In this new approach, shown in Figure 7-2, a conventional visor is coated with polymer-dispersed liquid crystal containing pleochroic dye molecules (i.e., a guest-host arrangement is used). The transmittance is controlled by a visor-mounted photosensor which measures the outside-scene luminance. After the pilot adjusts the transmittance to suit himself, the photosensor commands changes in transmittance, as needed, to hold constant retinal illuminance at the pilot's eye. The circuitry's time constant can be adjusted by the pilot to avoid overly rapid or overly slow response. A kill-switch may be included so that the pilot can command a clear visor quickly and easily.

All controls and batteries are contained in a small box, which connects to the visor via a thin cable that disconnects readily from the visor and carries no high voltages. In a completely integrated HMD system, the new quick disconnect connector and wiring harness system described in Section 4 would likely be used.

For purposes of this project, the visor has been designed as a stand-alone item so that it can be flight-tested. Its main purpose, however, is to enhance the contrast of an HMD under high ambient-illumination conditions while allowing adequate see-through visibility when outside luminance drops. If it was incorporated in an HMD, the control circuitry and power would probably be integrated with the HMD electronics.

Figure 7-3 presents a more detailed picture of variable transmittance visor basic operation. A thin, transparent layer of indium tin oxide (ITO) a transparent conducter, is applied to the inner surface of a standard visor. The ITO is coated with an emulsion of nematic liquid crystal, achromatic pleochroic dye, and polymer, which is cured to form a thin plastic coating. During the curing process, micro-droplets of liquid crystal and dye form spontaneously within the polymer matrix. Droplet size is consistent and can be controlled. A second layer of ITO is applied to the polymer skin and, finally, a protective polymer layer is placed over the second ITO layer since ITO coatings are delicate.

When no voltage is applied to the ITO electrodes, the liquid-crystal molecules (and, hence, the dye molecules) align themselves with the polymer wall within the spherical droplets. Consequently, the dye molecules face in many different directions and absorb light, making the visor dark. When full voltage is applied, the liquid-crystal and dye molecules align with the electrical field, which is perpendicular with the visor's surface. Consequently, the dye molecules do not absorb incoming light and the visor is clear. Intermediate voltages produce intermediate transmittances.

Conventional polymer-dispersed liquid crystal displays (LCDs) do not contain dye. Instead, they modulate light by scattering it, which is obviously unacceptable for a visor. In this design, scattering is minimized by using a liquid crystal having very low birefringence (0.08 or less) and matching its ordinary index of refraction with that of the polymer matrix and visor. Thus, the liquid crystal is inactive optically and serves only to control the orientation of the dye molecules, that modulate the light and reduce any residual scattering.

Ideally, the liquid crystal should operate in a fail-safe manner. Thus, it would respond to voltage in the opposite manner. That is, when no voltage is applied, it would align itself perpendicular with the visor surface and, when voltage is applied, it would align itself perpendicular with the electrical field and in random directions. This means that it would fail to a clear state. Polymer-dispersed liquid-crystal technology is relatively new and there are indications that the desired behavior can be developed eventually. For this project's

purposes, though, a clear-state failure mode will be achieved by incorporating a button battery on the visor. Should main power fail, this backup battery will take over and light a small warning LED on the visor's inner surface. The pilot will then have 30 minutes before, due to battery failure, the visor fails completely to its dark state.

CRT OPTIMIZATION for HMD USE and HMD-CRT INTEGRATION ISSUES

Among the most important circumstances affecting the design and selection of the CRT is FOV selection for the HMD. A frequently-levied requirement for the HMD is to have the sensor's FOV displayed in a direct 1-1 mapping on the HMD FOV. A requirement of this type for a panel-mounted presentation would clearly be waived, because the resulting cockpit-mounted display would be unacceptably large. Such a design requirement is feasible for the HMD, which, with its magnifications, can easily have an angular subtense to the eye (apparent FOV) this large. Further, if the display of more than one sensor input is required, and their associated FOVs are quite different, but their scan formats are similar, as is usually the case, then a primary sensor (normally the one used for pilotage tasks) must be chosen upon which the HMD design can be based. The display FOV is then selected to accommodate 1-1 mapping of the primary sensor's FOV. Display magnification (or minification) must usually be accepted in analog systems, for the display of any other sensors' information, because the dynamic range of the image source cannot usually support 1-1 mapping of all sensor presentations. It is also usually true that the sensor's line rate and pixel rate is taxing the miniature CRT's performance limits. Thus, the HMD FOV cannot be extended much, if at all, beyond the main sensor's FOV and be driven by the CRT with a 1:1 presentation of the sensor information without sacrificing the CRT's resolution and contrast performance.

Having accepted this criterion, one must determine its impact. Setting aside, for the moment, sensor/display system design issues, the major design considerations become the scanning format, the number of pixel elements spread over the HMD FOV, and the scan format/pixel rate capability of the image source. A number of approaches using quantitative methods are available for matching CRT performance based upon the FOV of the HMD. The approach chosen here relates HMD FOV (implied by the primary system sensor FOV), the system resolution resolution performance of the miniature CRT image source, and the addressable resolution elements available from a given imaging sensor, as shown in equation (7-1). These separate quantities are combined to calculate the desired horizontal FOV for 1-1 mapping of the sensor FOV on the HMD. Using equation 1, and some assumed CRT/sensor performance values, the desired horizontal FOV of the sensor display is determined to be 50 degrees.

$$\text{Hor FOV (deg)} = \frac{\{\text{CRT Format Size (mm)}\} \times \{\text{CRT Resolution (lp/mm)}\}}{\{17.5\ \text{(mrad/deg)}\} \times \{\text{Sensor Resolution (lp/mrad)}\}} \qquad (7\text{-}1)$$

Where: Assumed
CRT Spot Size = 19.0 microns (0.019mm) or 26 line pairs per millimeter (lp/mm)

Assumed
CRT Format Size = 19.0 millimeters

Assumed
Sensor Resolution = 0.57 line pairs per milliradian (lp/mrad)

∴ Hor FOV = ~50 degrees

Obviously, other considerations may affect the outcome. Some that come to mind are whether one or two CRTs will be used, and if the HMD FOV will be designed as a partially-overlapped or fully-overlapped system.

Vertical FOV relationships are also important, especially since human anatomical factors make a wide vertical FOV more difficult to obtain for pupil-forming HMD systems. Nominally, the monocular FOV of each eye's video channel might have a 4:3 aspect ratio, whose vertical FOV will be determined by its horizontal FOV and overlap condition, even though the total binocular presentation could differ significantly from such an aspect ratio.

It is important to consider other closely related factors whose origins are partially in the psychovisual domain and partially in the system designer's domain. The psychovisual considerations pertain most importantly to the required size of the subtended angle of display resolution elements to the eye, especially when such imagery is viewed in a vibrating environment. The basic assumption is that the vertical vibration component (normally having an orientation approximately perpendicular to the HMD scan lines), is the largest and most important component. Here, the literature relating to the viewing of HMDs, during vibration suggests that scan lines should subtend an angle to the eye of 2 to 4 arc minutes. This statement must be viewed with caution, since observer angular resolution is dependent on a number of interrelated factors, such as display luminance and contrast, which are not always specified with the data.

Display operating conditions also normally require that CRT scan line width be adjusted so that the scan line structure is not visible. However, sufficient dynamic range should be permitted between the minimum and maximum luminance levels, such that usable contrast is maintained between adjacent pixels imaged at different luminance levels on adjacent scan lines. To accomplish this goal, the display system designer needs to establish an acceptable scan line merge condition as shown in Figure 7-4. The merge condition selected should allow a reasonable tradeoff of scan structure contrast and vibration-induced artifacts which affect visibility of the scanned image. The CRT beam width conditions depicted in Figure 7-4 are 12 - 14 microns at the 50 percent response point. At night, display of sensor imagery at this condition is easily supported by current miniature CRTs. Given the previous example condition of 750 visible scan lines, the distance between scan lines has been adjusted to 18 - 19 microns. This allows scan lines to subtend about 3 arc minutes of visual angle for the 37.5 degree vertical FOV of the example HMD, which falls right between the 2-4 arc minute requirement suggested in the literature. Ideal Gaussian response is portrayed, although, for some miniature CRTs, the tails of each spot profile may, at certain CRT drive conditions, extend out to greater distances than indicated here. When adjusting CRT performance and HMD FOV to match or preserve most of the initial sensor performance, the designer usually wants to ensure that the scan line widths and merge conditions are adjusted to achieve minimum scan line structure modulation contrast (SLSMC), when adjacent pixels on adjacent scan lines are at peak luminance. Conversely, maximum modulation contrast is desired between adjacent scan lines, when every other scan line is at peak luminance levels and the adjacent pixels on adjacent scan lines are at their minimum luminance level. These relationships are shown, for two separate merge conditions in Figures 7-4a and 7-4b. A reasonable design procedure is to select a FOV and merge condition where, with adjacent scan lines at full luminance levels, the SLSMC is kept below the human operator's visual demand threshold for the modulation contrast/resolution conditions obtainable from the system. It should be obvious that the 40 percent merge condition represented by Figure 7-4b comes closest to meeting the stated criteria.

This above discussion can also lead one to consider the performance of some of the newer CRTs discussed in Section 4. In particular, some aircraft-sensor applications using relatively low line rates (i.e., 525 or 875 lines) for the night raster, but also needing high-luminance daylight symbology, capability might benefit from the use of a deceleration prefocus lens (DPFL) CRT. Preliminary performance results were given in Table 4-8. As already noted, this gun allows selectable efficiency and line widths that vary little over

significant modulation voltage ranges, perhaps permitting SLSMC criteria to be tailored for improved performance. For example, a DPFL CRT with a 14.25mm vertical format can accommodate 525 line raster imagery performance quite easily while still providing high luminance for daylight symbology displays.

CRT FORMAT SIZE

Fixing the size of the CRT format is a system design issue that should be, but often is not, given serious consideration. Increasing CRT size while holding the FOV of the HMD constant generally, has the benefit of improving the CRT's resolution and contrast performance, sometimes dramatically. As Table 4-1 indicates, CRT weight may not be increased substantially, although some dimensional penalty always accrues. The newer type of DPFL CRT gun offers the advantage of selectable gun efficiency and nearly constant linewidth performance over a significant range of modulation voltages. If the line rates are known for the design and have a reasonable range, then the CRT scan line structure and pixel spacing might be optimized to provide sufficient day/night operability for a given HMD application.

In relation to HMD optical design and aberration performance, increasing the CRT format size while holding FOV constant has two explicit effects. The first is that increasing CRT format size increases the focal length of the HMD optics. The second effect is that the f-number is also increased. In general, as the f-number is increased, the geometric optical aberrations of the system are decreased. Aberrations effected the most by an increase in f-number are spherical aberrations and coma, since they are inversely proportional to the $(\text{f-number})^4$ and $(\text{f-number})^3$, respectively. Obviously, a monochromatic HMD can benefit from larger CRT format sizes. Because the dominant aberration of polychromatic systems is transverse chromatic aberration, and because it is directly proportional to the FOV of the system times the system focal length, a completely diffractive optical system's aberration correction, at least, should benefit from a smaller CRT format size. How this applies in the general case needs careful study. We have a living, breathing example of a binocular 50 degree FOV optical design that was improved from a monochromatic design, using aspheres in the relay, and providing only 30 degrees of overlap, to a polychromatic design, with all spherical relay elements, and full overlap, simply by increasing the format size of the CRT 4mm. Thus, CRT design and HMD optical design parameters can be interrelated and their individual parameters should be set as part of a closed-loop design process.

CRT ACCELERATION POTENTIAL

Figure 7-5 depicts the improvement in linewidth of a CRT, as anode potential increased, but where no optimization of the CRT phosphor characteristics versus final anode potential was considered. Clearly, higher anode potentials can improve resolution regardless of the application. If the QDC wiring harness system described in section 4 is successful, then there is less reason than ever not to adopt CRT optimization at the higher anode potentials, as a function of CRT size and anode level limits. A minor drawback is that more deflection power will be required within the display electronics to slew the electron beam across the entire CRT format.

CRT PHOSPHOR SELECTION

CRT phosphor selection can be an important factor in achieving superior CRT resolution and contrast performance. By selection, we mean more than just picking P43, P53, etc. We also mean the methods by which the phosphor is designed, processed, and deposited on the CRT faceplate by a particular CRT manufacturer.

Figure 7-6 shows the cross sectional view of a typical particulate phosphor screen. To achieve good area coverage of the faceplate with a particulate phosphor, particles of different sizes may be mixed in specific proportions to optimize resolution and luminous

efficiency. For a sputtered phosphor, particle size can be much smaller and more uniform, but generally (at least until more development work is performed with the annealing processes for sputtered phosphors) they provide less luminance for a given power input than do the best particulate phosphors. For a particulate phosphor screen, density must be carefully controlled to maximize energy capture from the electron beam while minimizing light scattering through the phosphor matrix.

Figure 7-7 shows that screen density and resolution have an interrelationship that must be optimized. Anode potential and other factors will cause the curve to undergo a translation between absolute values for screen density/resolution, but the general shape and, therefore, the optimization of the two parameters, still holds. The implications are that if you want to obtain more optimum performance from your HMD system, take time to inform yourself as to how the CRT vendor optimizes his version of some phosphor type that you have selected, and operate your display electronics at the anode potential for which the phosphor/faceplate system was designed and produced.

CRT CUTOFF

Cutoff voltages for miniature CRTs can vary over a significant voltage range. The Air Force Armstrong Laboratory has versions of 27mm CRTs whose cutoff voltages range as low as 60 volts to as high as 123 volts. Invariably, better resolution is achievable with high cutoff CRTs. The improvement is not a direct result of high cutoff, but results when the CRT's triode parameters are adjusted for high resolution performance, giving rise to higher cutoff voltages. Greater drive voltages over large bandwidths are hard to support, especially for HMD systems where the CRT and final video amplification stage of its drive electronics are separated by relatively large distances (six to eight feet). Setting this parameter must be given special consideration, and obviously depends upon the design and performance of the interface cable and electronics.

CRT-CABLE-ELECTRONICS

The maximum resolution performance that a CRT may be capable of providing may not be possible if the cable and electronics interface is incapable of providing the signal modulation and bandwidth required to utilize the full dynamic range of the CRT. Figures 7-8 and 7-9 show how visual acuity for the display varies with the display (CRT) resolution for HMDs with assumed FOVs of 30 degrees and 40 degrees. A fundamental factor affecting display resolution is the performance and design of the video amplification stage electronics and the signal conduit.

Often, high bandwidth video (e.g., 1225 line 2:1 interlace raster video) is input to the cable/CRT combination and assumed to be available on the HMD. As Figure 7-10 shows, the bandwidth available with standard six and eight foot CRT cables is woefully inadequate (due mainly to the distributed capacitance along the cable) for providing video bandwidths of about 30 mHz and beyond.

One solution sometimes employed is to mount the final video amplification stage on the helmet near the CRT. This only adds to already severe helmet weight problems, and power dissipation can also be significant. A compromise for improving cable video transmission limitations is to mount the final video amplification stages at some intermediate point, such as in the QDC and wiring harness assembly, whose development was mentioned in section 4. Thus cable length can be held to about 18 inches, leaving the total reactive impedance that must be driven at more manageable levels.

Actually, the problem is being approached conservatively through the design of a video processor-video amplifier hybrid chip pair. The video processor hybrid would reside in the display electronics and drive a terminated transmission line between itself and the QDC-mounted video amplifier hybrid. The video amplifier hybrid then drives an

unterminated link to the CRT using a single-ended cathode drive. Cathode drive was selected to prevent modulation at the G1 grid that might affect the G1-G2 field potentials that determine the crossover size in the triode section of the CRT's electron gun. Design goals for the hybrid pair are shown in Table 7-1. The levels selected are both consistent with expected demands for HMD operational performance, as well as limitations with current technology. DC restoration and other functions are being included to make full-functioned calligraphic and raster performance possible

A question often raised concerning this issue is why not provide a low-loss terminated transmission line between the video amplifier and the CRT. A quick pass through the relationships at work for this problem indicates why a terminated transmission line scheme is probably not the best choice, especially at peak modulation values of 50 volts. Assume an output impedance (Ro) for the amplifier of 50 ohms and a 100 ohm termination (ZL) at the CRT. The modulation voltage at the amplifier (Vm) then must be 75 volts (25 volts across its output impedance) to get 50 volts modulation at the load (CRT).

Thus: $$I_{out} = \frac{V_m}{R_o + Z_L} \dashrightarrow I_{max} = \frac{50v}{100\Omega} = 0.5 \text{ amps}$$

And: $$P_t = (0.5 \text{ amp})(75 \text{volts}) = 37.5 \text{ watts}$$

This level of power dissipation, which is released as heat, in the final amplification stage is obviously too high for torso mounting. A terminated 100Ω load at the CRT would end up having to dissipate 25 watts. Power dissipation levels of this magnitude are far too high for the current state of helmet system technology. Figure 7-11 depicts the measured values for the prototype video processor-amplifier pair and the expected values for the production version of the hybrid.

THE CRT DISPLAY ELECTRONICS

Although sometimes given secondary consideration, the CRT drive electronics are extremely important components, for virtual panoramic display (VPD) HMD applications. Their performance is a fundamental factor in the modulation transfer function (MTF) that the CRT can attain. The drive electronics also control most of the important factors relating to the customization/ integration of the CRT formats with respect to the optical design.

DEFLECTION SYSTEM ISSUES

CRT-TO-OPTICS MAPPING CORRECTION

As the discussion associated with Figure 4-4 has already explained, the F-theta mapped optics produce a type of pincushion distortion which must be corrected by implementing barrel distortion of the CRT image format. Partially overlapped optics, which have their optical axes turned out, can also produce mild perspective distortion which is trapezoidal in form. Ordinarily, such distortions could be specified by the optical designer and the system designer could insert the appropriate corrections using a truncated polynomial approximation with sufficient correction terms in dedicated correction circuitry associated with the deflection subsystem. However, given the variation experienced between individual CRT electron optics, the deflection yoke, and the physical alignment of the deflection yokes with the electron optics during the manufacturing process, these ideal conditions cannot be obtained. Therefore, each CRT must be calibrated for the particular HMD design, and the correction coefficients recorded and entered into the control elements of the CRT electronics. HMD optical systems exist that require correction terms out to the fifth order. Correction terms to this order can have a significant impact on the CRT

deflection circuitry complexity and the perceived 'noise' in the deflections. Adding second order terms admittedly has the greatest impact by doubling the bandwidth over that required for the linear terms, but, by the time fifth order terms are reached, bandwidth requirements have been more than tripled. The geometry correction terms most often used out to third order terms and their effects are shown in Figure 7-12.

DEROTATION

For HMD applications, it is sometimes desired that the display format be maintained at the proper orientation with respect to the aircraft's or simulator's roll axis, regardless of the roll orientation of the head, and therefore, the display presentation. Maintaining the proper orientation is usually accomplished through the use of roll sensing provided by a helmet-orientation/position measurement system whose roll output is fed directly to the drive electronics or, if a two or three-dimensional graphics processor is being used, directly to that subsystem. As shown in Figure 7-13, for a partially overlapped, 50 degree binocular system, the visual center of the optics is off center from the CRT, and the derotation to be performed involves both a translation and a derotation on the CRT. Particular characteristics are set by the VPD design conditions. This correction must be performed at the field rate at which the display is refreshed. As discussed in Section 4, derotation of raster imagery is usually performed by the CRT electronics. Derotation of vector graphic symbology is best accomplished at its source, and then transmitted in corrected form to the CRT drive electronics.

CALLIGRAPHIC SYSTEM PERFORMANCE

Figure 7-14 depicts some preliminary results with newer CRTs that indicate that, along with the proper gun, cathode, and phosphor design, refresh rates may be modified to improve luminance performance. For daylight symbology presentation, a display electronics providing refresh rates that are variable, may greatly improve display contrast, especially, as is often the case for HMD symbology presentation, if the symbology requirements dictate minimal presentations.

Also, as can be observed from Figure 7-13, the CRT is overscanned in the horizontal direction to (1) obtain the largest format possible with a given CRT faceplate size for the normal 4:3 aspect ratio, and to (2) ease the optical design problem. To prevent damage at the edge of the CRT caused by electron beam heating, the beam must be blanked (turned off) automatically at a given radial distance, using an operating mode normally referred to as 'circular blanking'. The extinction of the e-beam is controlled by its radial distance from the deflection center of the CRT, based upon CRT quality area size and any additional active deflection correction control. There are several methods employed to accomplish circular blanking, however, methods that employ slow square root circuitry are to be avoided.

Due to the high resolution of the magnified CRT format imposed by the VPD FOV conditions; where the same image point is transmitted to each eye through different portions of a partially overlapped optical system, on-axis deflection linearity is critical. Linearity is usually specified to be in the range of 0.5 to 0.25 percent. To achieve such linearity with miniature CRTs, a class-A linear deflection amplifier design is normally required. Class A amplifiers cause heat dissipation to become an important design issue. CRT design which stresses higher acceleration potentials and, therefore, stiffer (higher voltage) e-beams, exacerbates this problem. To support this performance, low capacitance cabling and low inductance/capacitance, high current deflection yokes using only ferrite cores are employed.

ELECTRONIC ALIGNMENT

As previously discussed, some electronic alignment must be performed, to correct for residual errors in the alignment of the optics and in the reproducible characteristics of

individual CRTs. Although complex alignment patterns have been employed to carefully check the exact horizontal/vertical alignment of partially overlapped binocular displays, the simple patterns shown in Figure 7-15a and 7-15b are usually sufficient. The pattern shown in Figure 7-15a has been recommended in the literature, however the pattern shown in Figure 7-15b appears to sometimes produce better results, because there are no identical structures presented to both eyes which the eyes might attempt to converge to identical retinal correspondence points. In addition, the pattern shown in 7-15b provides an exact endpoint match capability not provided by some of the open reticle patterns, which provide only horizontal lines to one eye and vertical lines to the other. Also, actual use with subjects has shown that these patterns must be flashed in order to prevent improper eye convergence to the display/image. A duty cycle pattern that seems to work well is to repetitively flash the patterns on for about 75 milliseconds, followed by a 100 to 125 millisecond dark period. However, some subjects experience drift and cannot perform the electronic alignment efficiently using a pattern like 7-15b. Research is still ongoing for determining a better approach for performing this type of alignment function.

POWER SUPPLY PERFORMANCE

The HMD optics magnify the CRT faceplate imagery to obtain the required angular FOV at the users eye from 4 to 19 times. Magnifications of this order are sufficient to make electron beam spot noise, raster line jitter and drive electronics power supply noise both noticeable and objectionable. This makes power supply noise and regulation specifications very important.

The interaction of the CRT drive electronic's power supply noise and ripple with the display imagery can produce complex effects. These artifacts produce movement of the display imagery visible to the human operator, depending upon their frequency and amplitude, as a function of angular subtense on the display. This is particularly true for military power supplies that utilize high frequency switching designs. As an example, consider the implementation of an 875 line, 2:1 interlace scan format on an HMD with a 30 degree horizontal FOV. The scan line 'on time' for an 875 line rate is approximately 31.3 microseconds, which implies that one degree on the display equals about one microsecond. As shown in Figure 7-16, visual contrast sensitivity peaks at about one to three cycles per degree. A switching power supply with a ripple frequency of one to two megahertz has a switching frequency that could cause cyclical patterns at frequencies where the eye is most sensitive. Alternatively, a switching supply operating at 200 kilohertz or 10 mHz, may be sufficiently removed, if ripple amplitude is low enough, to moderate such effects. The point here is that interactions of this type should be thoroughly investigated for all anticipated operating conditions.

THE HMT

Many integration issues were already alluded to in Section 5. Delving into the complexities of integration any further is beyond the scope of this half day course. It is also true that new optical HMT systems are just becoming available and have not been evaluated, making a comprehensive and fair coverage of these issues impossible at this time. Some additional information on magnetic sighting system integration issues can be found in reference (03).

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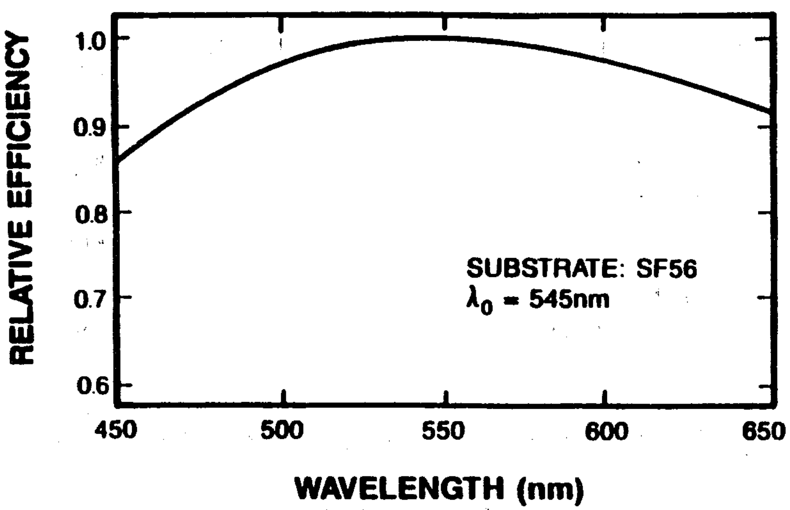
Cotton, C. T., Faklis, D., Bowen, J. P., and Morris, G. M., Application of Surface-Relief Diffractive Optics to Helmet Mounted Displays, Rochester Photonics Corp. under contract F41622-90-C-1013, USAF Armstrong Laboratory, March, 1991.

Kocian, D. F. Visually Coupled Systems (VCS): Preparing the Engineering Research Framework, IEEE, AESS, 11th Annual Dayton, Ohio Chapter Symposium, 28 November, 1990.

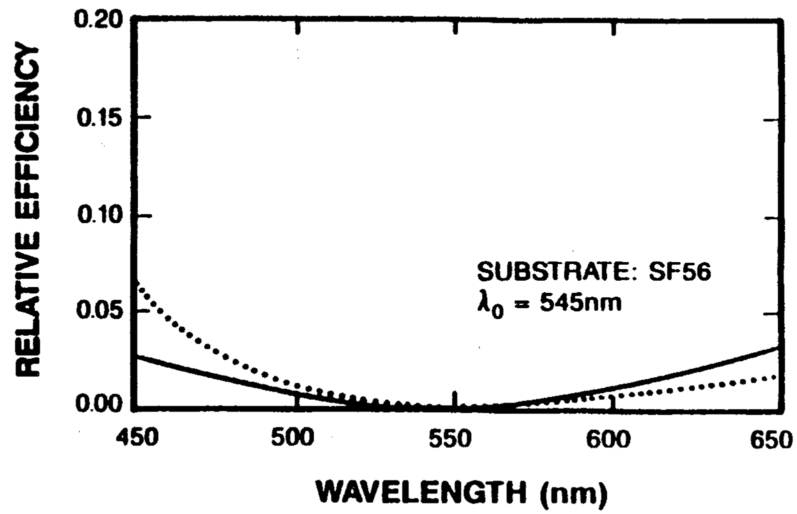
Kocian, D.F., Design Considerations for Virtual Panoramic Display (VPD) Helmet Systems, AGARD Symposium on The Man-Machine Interface in Tactical Aircraft Design and Combat Automation, AGARD-CP-425, July, 1988.

Task, H.L., Kocian, D.F., and Brindle, J.H., Helmet Mounted Displays: Design Considerations, Advancement on Visualization Techniques, AGARDograph No. 255, October 1980.

FIGURE 7-1
REPRESENTATIVE SRD OPTICS' WAVELENGTH DEPENDENCE RESULTS FOR HMDs



7-1a THE RELATIVE EFFICIENCY FOR THE m = 1 ORDER. THE EFFICIENCY PEAKS AT THE DESIGN WAVELENGTH, AND FALLS OFF TO EITHER SIDE.



7-1b THE RELATIVE AMOUNTS OF POWER DIFFRACTED INTO THE m = 0 AND m = 2 ORDERS. THIS LIGHT CONSTITUTES A BACKGROUND THAT DECREASES THE OVERALL SYSTEM PERFORMANCE.

DFK-92-3-18

FIGURE 7-2
VARIABLE TRANSMITTANCE VISOR

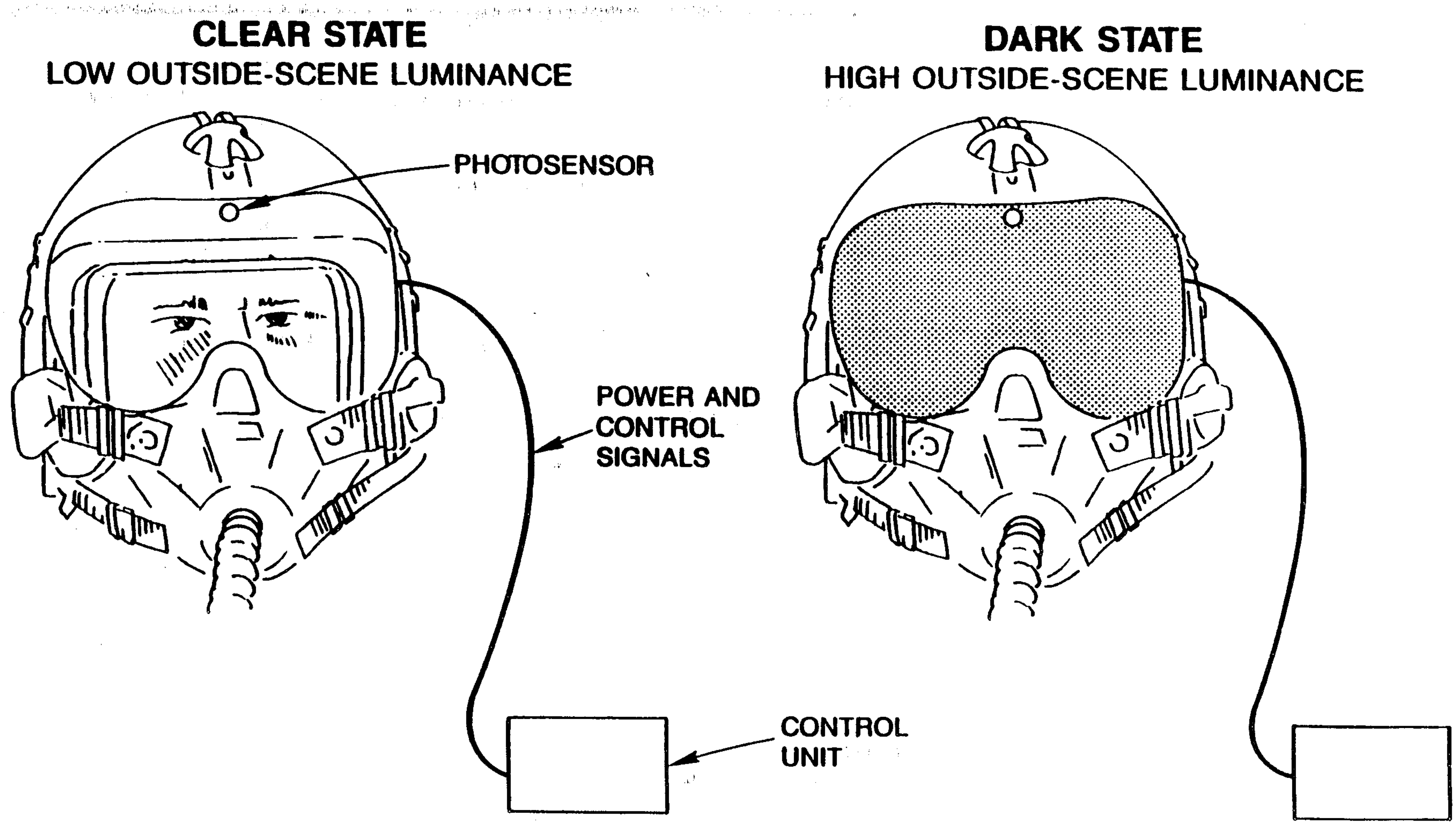
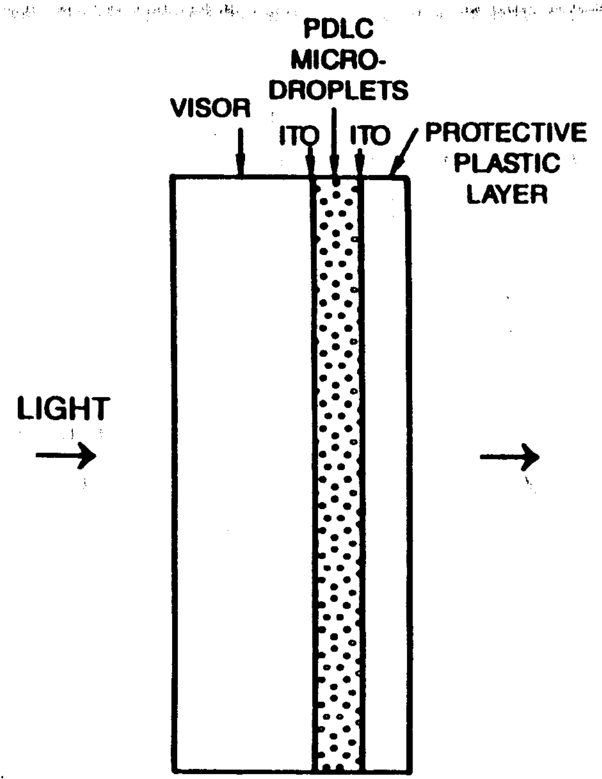
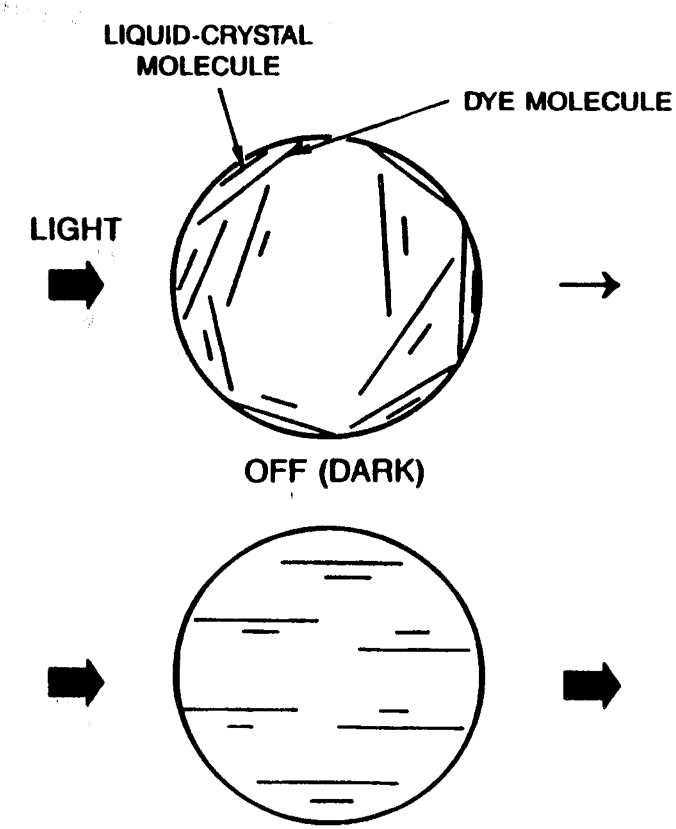


FIGURE 7-3
VARIABLE-TRANSMITTANCE VISOR SCHEMATIC



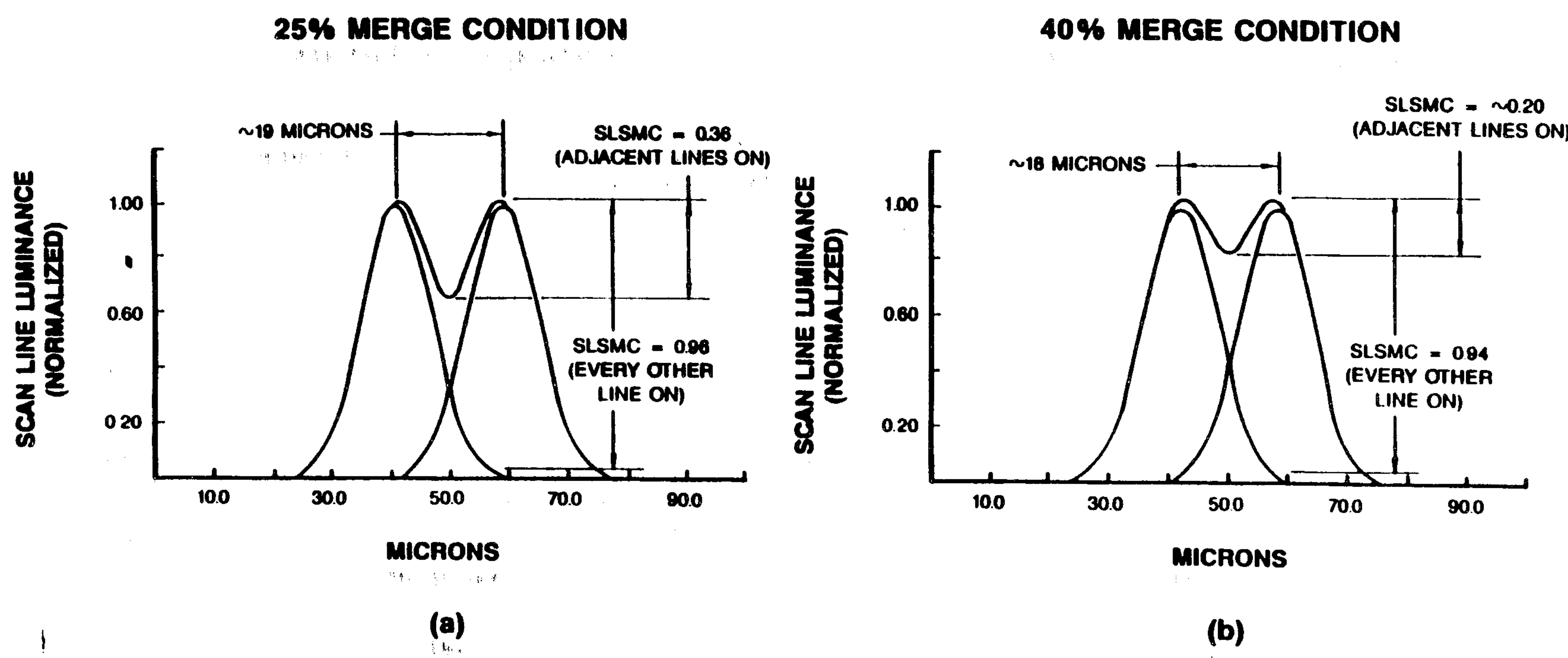
BASIC STRUCTURE
(LAYER THICKNESS NOT DRAWN TO SCALE)



ENLARGED VIEW OF A SINGLE MICRO-DROPLET

HE-91-3 8

FIGURE 7-4
IMPACT OF MERGE POINT SELECTION FOR ADJACENT SCAN LINES



SLSMC = SCAN LINE STRUCTURE MODULATION CONTRAST

FIGURE 7-5

CRT LINE PROFILES FOR 7kV and 9kV ANODE POTENTIALS

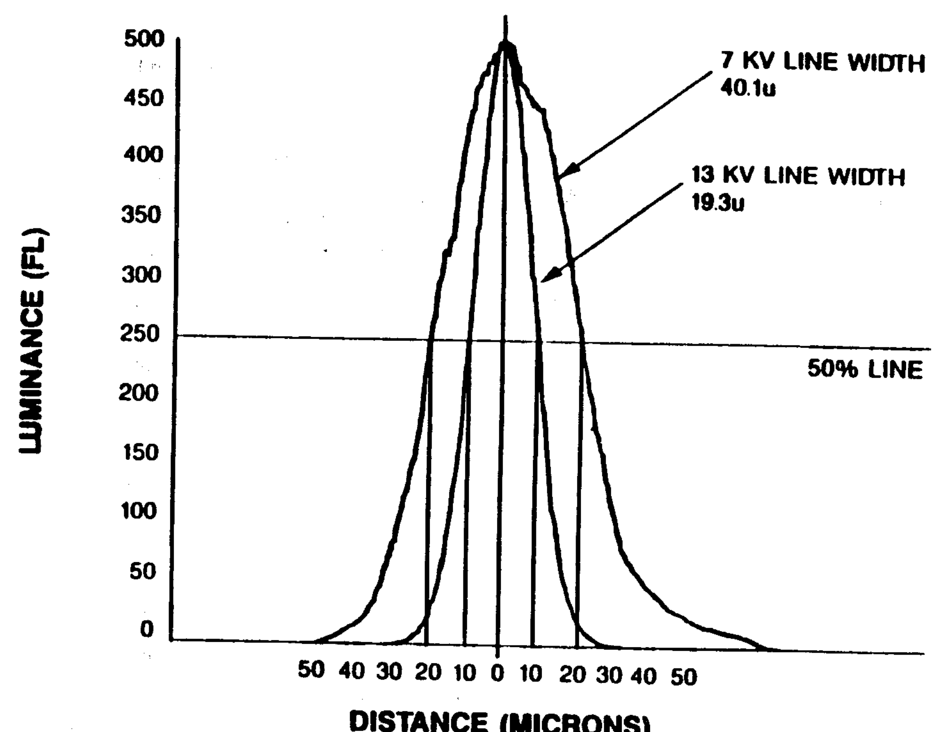


FIGURE 7-6
IDEALIZED CROSS SECTIONAL VIEW OF CRT PHOSPHOR

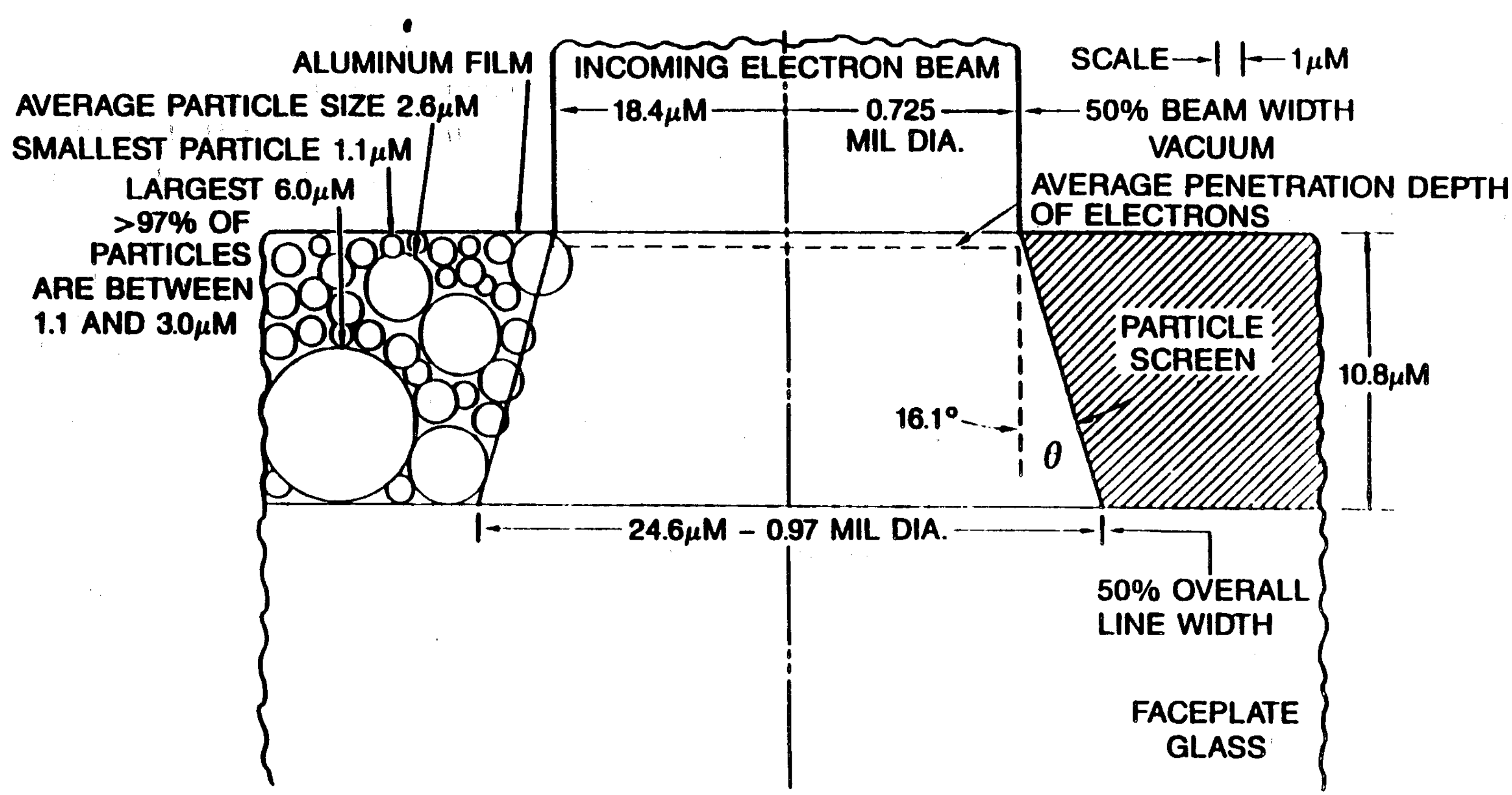


FIGURE 7-7
TAILORING THE PERFORMANCE OF THE CRT PHOSPHOR SCREEN

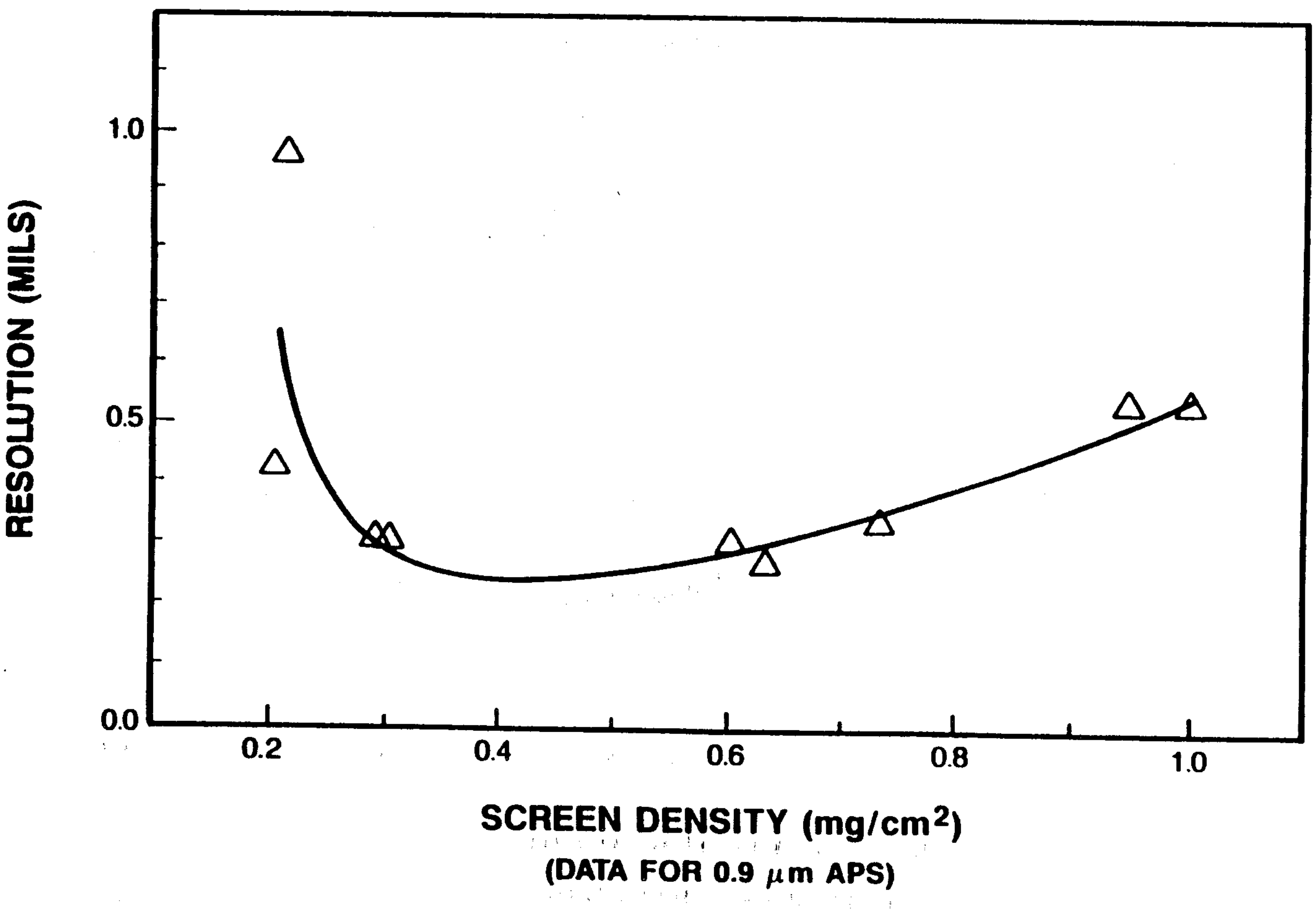


FIGURE 7-8

Visual Resolution vs Display Resolution for a HMD with 30 Degree FOV

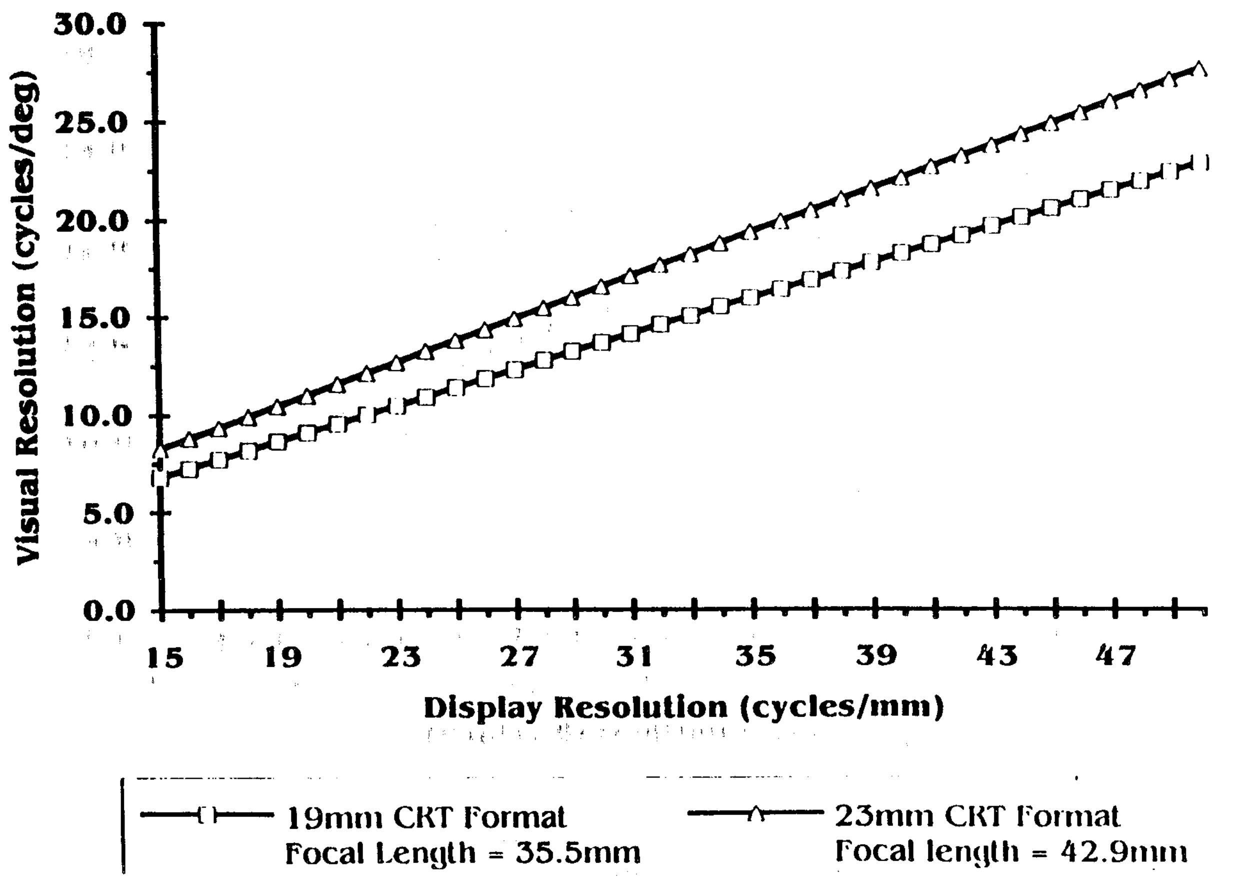


FIGURE 7-9

Visual Resolution vs Display Resolution for a HMD with 40 Degree FOV

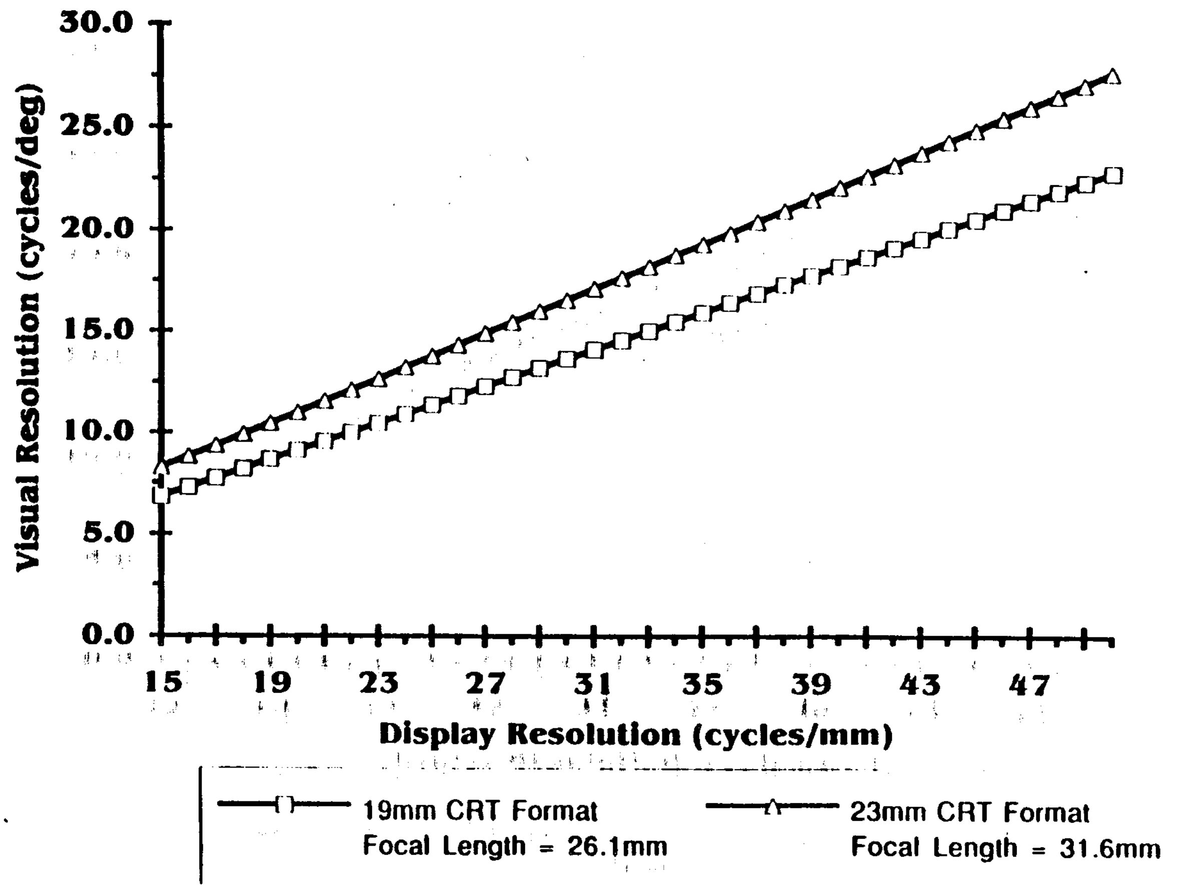


FIGURE 7-10
FREQUENCY RESPONSE CURVE OF THE CABLE/ELECTRONICS COMBINATION

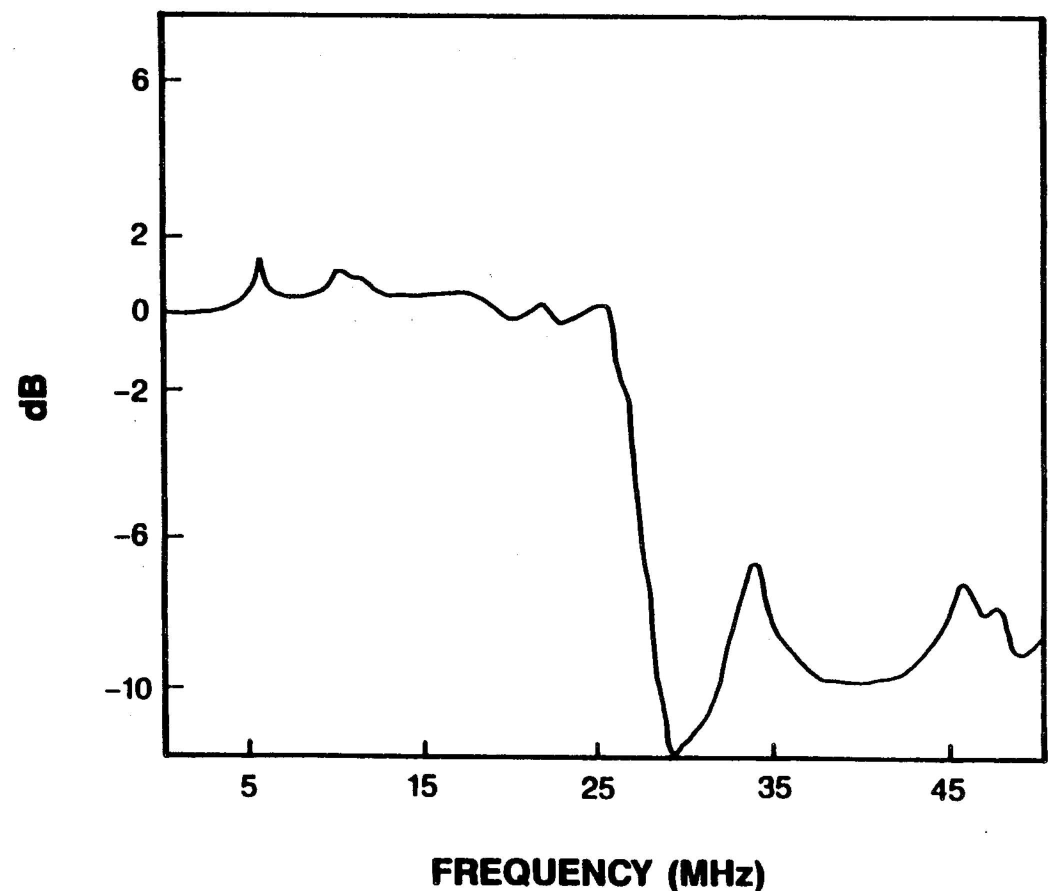


TABLE 7-1

Video Hybrid Chip Set Design Goals

Video Processsor		Video Amplifier	
Parameter	**Design Goal**	**Parameter**	**Design Goal**
Frequency Response	150 MHz	Frequency Response	100 MHz
Gain Flatness	+/- 1.0 dB	Gain Flatness	+/- 1.0 dB
Step Response	2.33 nsec	Step Response	3.5 nsec
		Output Swing	48-50 Volts P-P

FIGURE 7-11
FREQUENCY RESPONSE FOR HYBRID VIDEO PROCESSOR / VIDEO AMPLIFIER

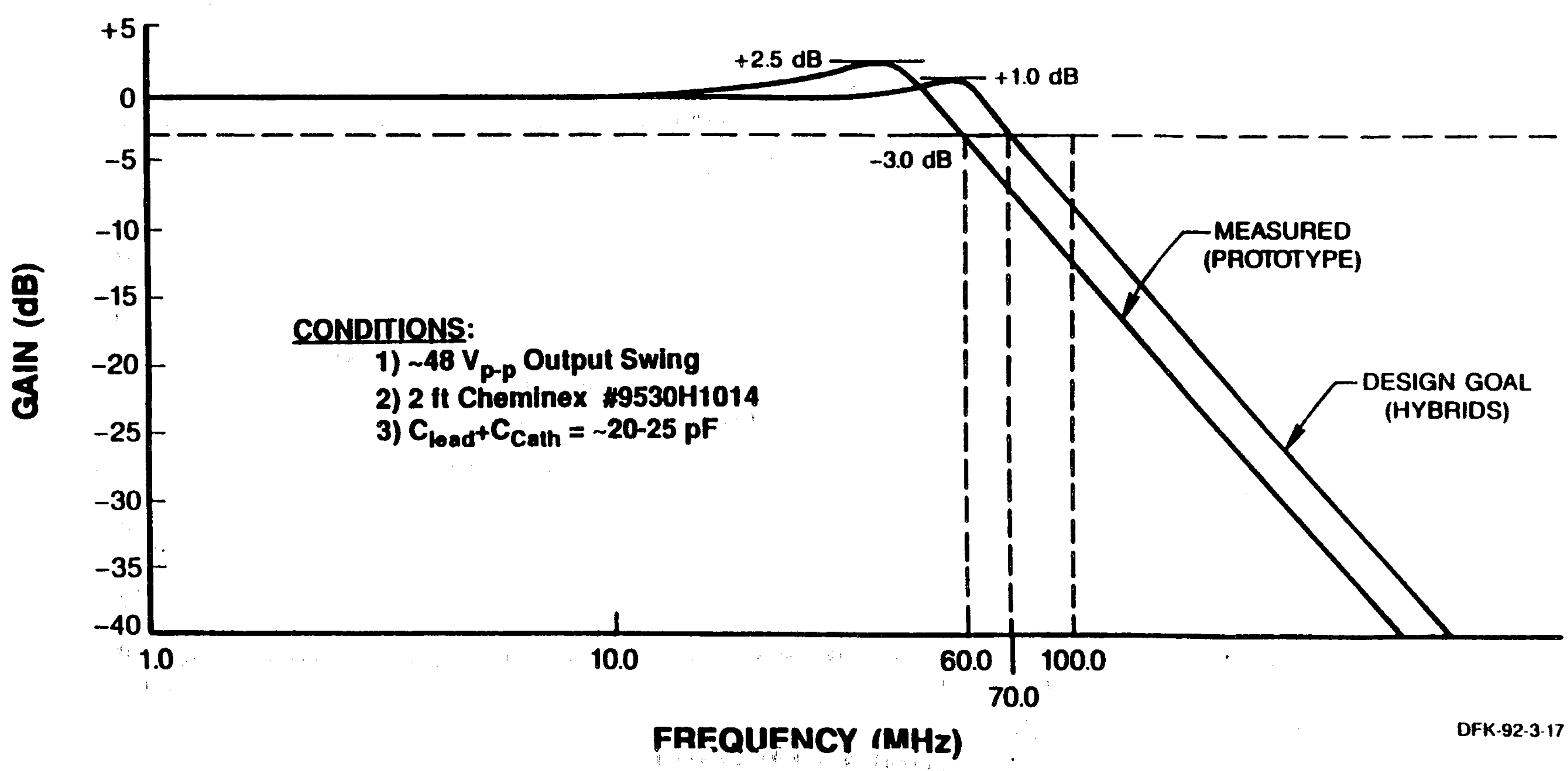


FIGURE 7-12
GEOMETRY CORRECTION TERMS for CRT ELECTRONICS

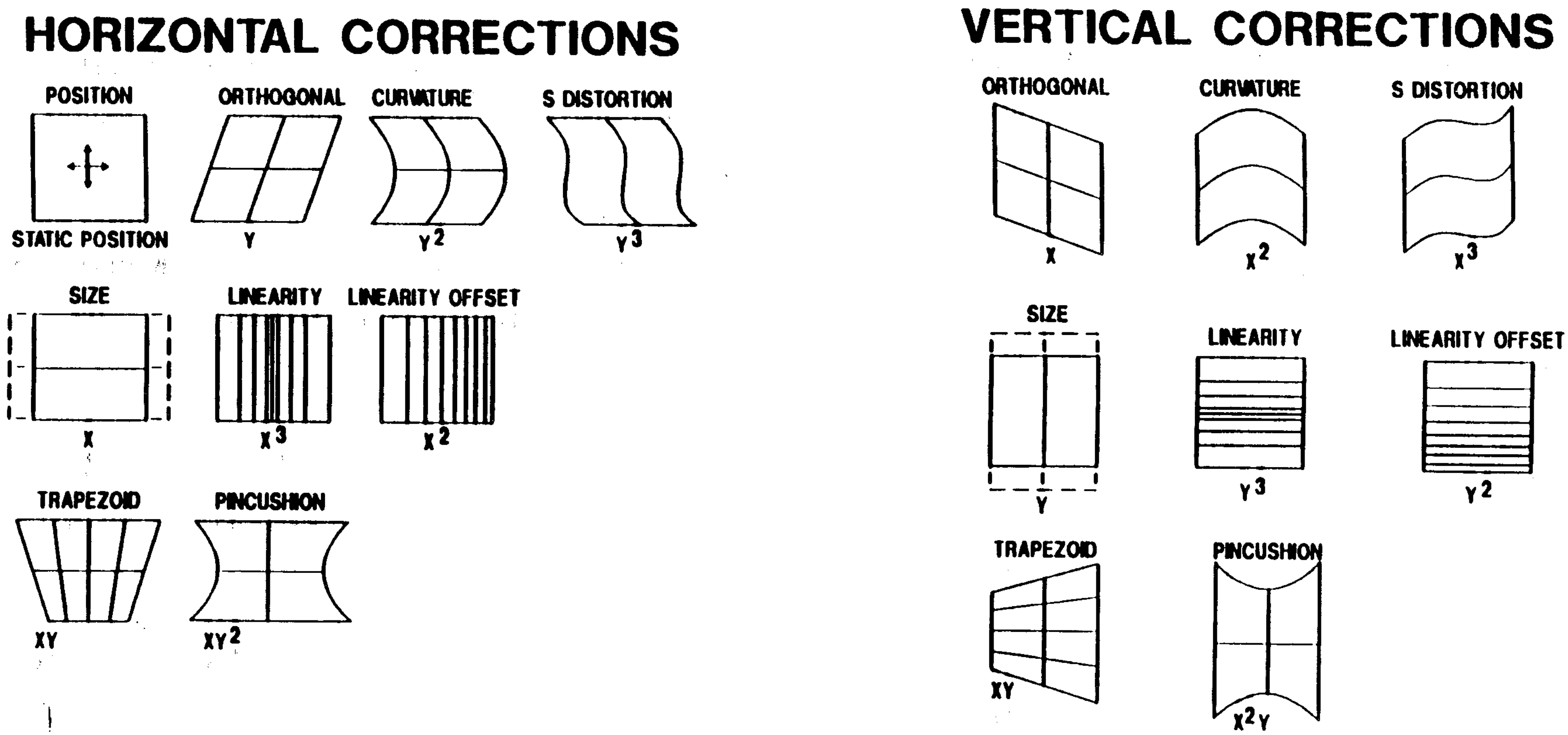
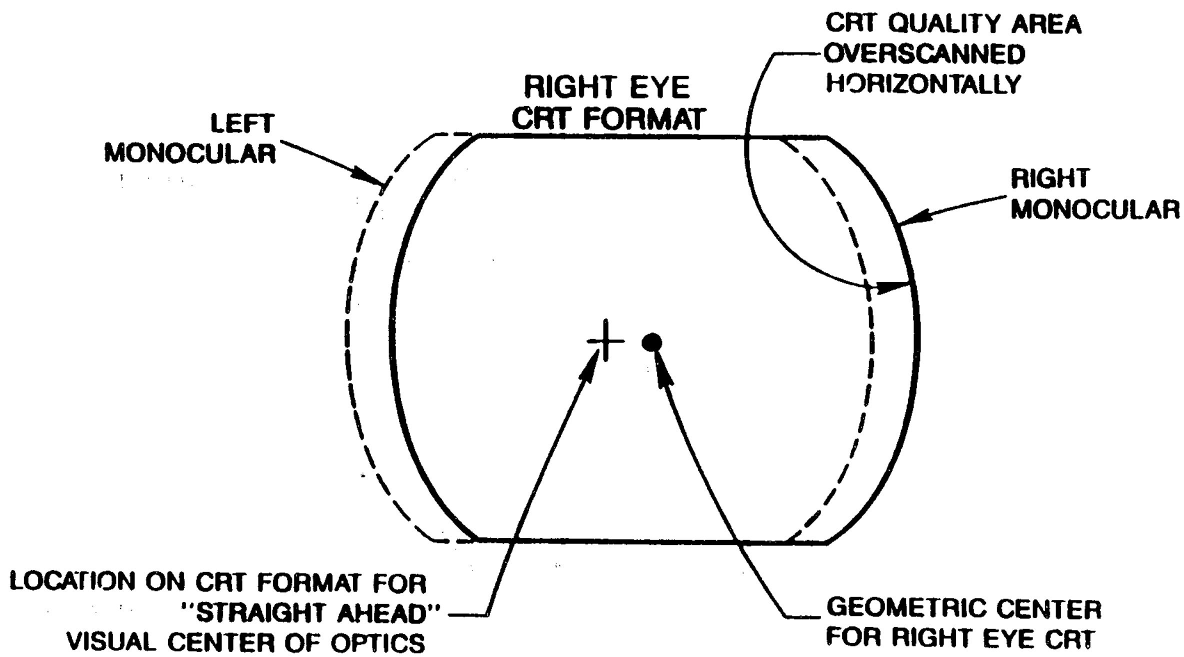


FIGURE 7-13
CRT SCAN FORMAT for BINOCULAR HMD



OPTICS MONOCULAR FOV = 44° HOR × 33° VER
BINOCULAR OVERLAP FOV = 50° HOR

FIGURE 7-14
SOME INTERESTING PRELIMINARY RESULTS WITH THE DPFL CRT

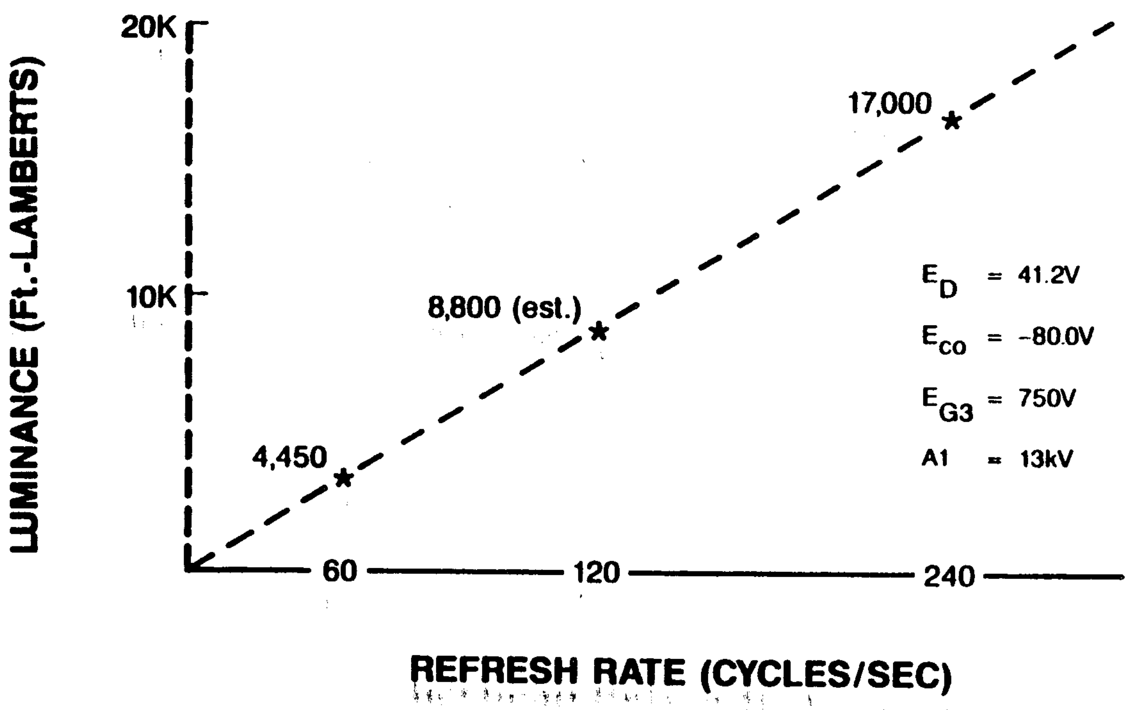


FIGURE 7-15
BINOCULAR DISPLAY ALIGNMENT PATTERNS

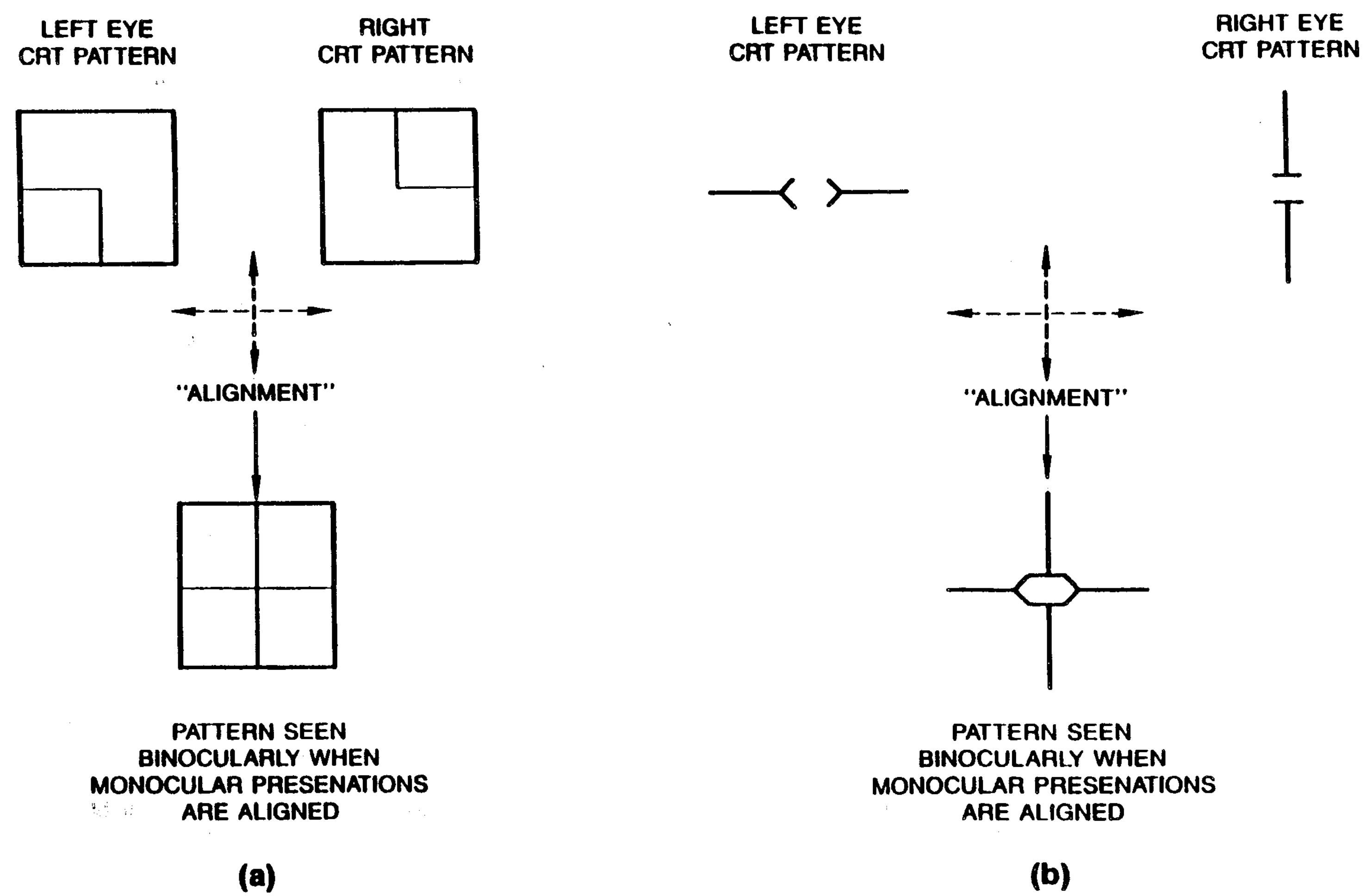


FIGURE 7-16
AVERAGE CONTRAST SENSITIVITY CURVE (J CURVE) FOR HUMAN EYE